

THE EFFECT OF THE COMPOSITION OF METAL-CERAMIC POWDERS ON THE STRUCTURE AND PERFORMANCE PROPERTIES OF COATINGS OBTAINED BY THE HVOF METHOD

Arystanbek Kusainov ¹, Yermakhan Molbosynov ^{1*}, Indira Abizhanova ¹,
Rashid Kuanyshbay ², Abai Alimov ²

¹NJSC "D. Serikbayev East Kazakhstan Technical University", Ust-Kamenogorsk, Kazakhstan

²LLP "PlasmaScience", Ust-Kamenogorsk, Kazakhstan

*Corresponding author: Molbosynov Yermakhan Serikuly, e-mail: mr.molbosunov@gmail.com

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HVOF spraying; cermet coatings; WC-Co-Cr; WC-NiCr; WC-Ni; Cr₃C₂-NiCr; Al₂O₃-NiCr; microstructure; SEM/EDS analysis; microhardness; coefficient of friction; scratch test; adhesive strength; surface roughness; wear resistance.

ABSTRACT

The article presents the results of a comprehensive study of WC-Co-Cr, WC-NiCr, WC-Ni, Cr₃C₂-NiCr, and Al₂O₃-NiCr cermet coatings deposited onto a 65G steel substrate by the high-velocity oxy-fuel (HVOF) spraying method. An analysis of the microstructure (SEM/EDS), microhardness, surface roughness, tribological characteristics, and adhesive strength of the coatings was carried out. It was established that the composition of the powder mixture and the characteristics of the binder phase significantly affect the formation of the structure and performance properties of the coatings.

The WC-Co-Cr coating formed the densest and most structurally homogeneous lamellar structure, demonstrating the lowest coefficient of friction ($\mu = 0.143$), the highest microhardness (1316.87 HV), and high resistance to scratch loading. The Cr₃C₂-NiCr and WC-NiCr coatings showed satisfactory tribological characteristics ($\mu = 0.310$ and 0.326 , respectively); however, reduced adhesive strength was observed for the Cr₃C₂-NiCr coating. The WC-Ni coating was characterized by an increased coefficient of friction (0.545) at moderate hardness values (721.2 HV). The highest coefficient of friction was found for the Al₂O₃-NiCr coating (0.630), while this system also demonstrated the lowest microhardness (631.59 HV) and instability in structure formation.

The surface roughness of the coatings was in the range of $R_a = 3.881$ – $8.130 \mu\text{m}$ and depended on the spraying conditions. The obtained results made it possible to determine that the WC-Co-Cr coating provides the optimal combination of mechanical and tribological properties and is the most promising for application under conditions of intensive abrasive-adhesive wear in mechanical engineering, power engineering, and metallurgy.

INTRODUCTION

The modern metalworking industry places increasing demands on the wear resistance, corrosion resistance, and durability of metal components operating under severe mechanical and thermal loading conditions. One of the most effective approaches to extending the service life of such components is the application of protective coatings that enhance the performance of friction



units and other critical structural elements. In the present study, high-velocity oxygen-fuel (HVOF) spraying technology was employed to produce the coatings, as this method enables the formation of dense coatings with low porosity, high adhesive strength, and minimal particle oxidation owing to the acceleration of powder particles in a supersonic gas jet.

The investigated coating systems included the metal-ceramic compositions WC–Co–Cr, WC–NiCr, WC–Ni, Cr_3C_2 –NiCr, and Al_2O_3 –NiCr, which are widely recognized for their high hardness, heat resistance, and excellent resistance to abrasive and erosive wear. The relevance of this study is determined by the need to optimize the technological parameters of the HVOF process, including the fuel-to-oxygen ratio, gas pressure, spray distance, and powder feed rate, since these parameters strongly influence the microstructure, thickness, porosity, hardness, surface roughness, and adhesive strength of the resulting coatings. Accordingly, the present work includes a comprehensive investigation of coating microstructure, microhardness, roughness, and adhesive strength obtained under different spraying conditions in order to establish the optimal processing parameters for engineering applications in the mechanical, metallurgical, and energy industries.

Recent studies demonstrate that WC–Co–Cr coatings remain among the most effective HVOF-deposited materials due to their excellent combination of hardness, wear resistance, and mechanical integrity. Nie et al. (2024) reported that WC–10Co–4Cr coatings deposited on heat-treated steel substrates reached microhardness values of up to 1203 HV while reducing field wear of agricultural components by more than 60%. Similarly, Shu et al. (2022) obtained hardness values of approximately 1300 HV and bonding strengths of 70 MPa for WC–10Co–4Cr coatings applied to Ti–6Al–4V substrates. Książek et al. (2021) further demonstrated that chromium additions strengthen the cobalt binder, resulting in improved mechanical properties and enhanced slurry-erosion resistance. Process-level optimization of HVOF spraying parameters for WC–Co-based coatings has also been addressed through numerical and experimental approaches, including modeling of nano-WC deposition on magnesium alloy substrates (Wang, X. et al., 2026) and surface-property optimization of NiCr/WC–Co coatings (Luo & Jean, 2026).

The influence of binder composition has also been extensively investigated in chromium-carbide-based coatings. Ksiazek and Łyp-Wrońska (2024) showed that incorporating cobalt into Cr_3C_2 –NiCr feedstock promotes the formation of a denser lamellar microstructure, thereby increasing hardness and scratch adhesion. In contrast, Ksiazek and Boron (2025) found that replacing cobalt with nickel enhances ductility and corrosion resistance but reduces maximum hardness, illustrating the trade-off between mechanical strength and toughness. A comprehensive review by Seitov et al. (2025) further identified porosity and carbide dissolution as the principal microstructural factors governing the tribological performance of Cr_3C_2 –NiCr coatings. In addition, He et al. (2022) demonstrated that the selection of an appropriate bond coat significantly influences the fatigue-corrosion performance of Cr_3C_2 –NiCr coating systems, emphasizing the importance of coating architecture for structural applications. Complementary studies on Cr_3C_2 -based systems have examined hot corrosion and cyclic oxidation behavior of CoMoCrSi + Cr_3C_2 coatings (S. et al., 2026), oxidation-dominated high-temperature wear mechanisms in Cr_3C_2 –NiCr coatings (Ma & Ruggero, 2026), and the wear-corrosion performance of WC– Cr_3C_2 composite coatings in industrial separator applications (Yang et al., 2024). The influence of binder chemistry extends beyond flame and HVOF spraying: detonation-sprayed WC coatings with Co–Cr, Ni, and NiCr binders show similar composition-dependent trends in hardness and wear resistance (Magazov et al., 2026).

Nickel-based and oxide-reinforced coatings have likewise attracted considerable attention. Bochenek et al. (2022) compared HVOF spraying, atmospheric plasma spraying, and laser cladding for NiCr–Re– Al_2O_3 coatings and concluded that HVOF produced the lowest residual stresses together with the most favorable combination of hardness and wear resistance. These

findings support the selection of HVOF processing for the Al_2O_3 -NiCr coating investigated in the present work. Furthermore, Qiao et al. (2024) demonstrated that laser remelting of WC-Ni coatings substantially modifies the coating microstructure and improves wear resistance, highlighting that optimization of the metallic binder phase is often as important as the carbide reinforcement itself. The durability of HVOF coatings under thermal and oxidative loading has also been studied for bond-coat and thermal-barrier systems, including high-entropy alloy bond coats designed with the CALPHAD approach (Boschen et al., 2026) and MCrAlY/YSZ thermal barrier coatings (Chen et al., 2025).

Despite these advances, most published studies have focused on the optimization of individual coating systems under different spraying conditions, substrate materials, and testing methodologies. Consequently, direct comparisons of WC-Co-Cr, WC-NiCr, WC-Ni, Cr_3C_2 -NiCr, and Al_2O_3 -NiCr coatings deposited under identical HVOF conditions on the same substrate remain scarce, limiting a systematic understanding of how binder chemistry influences hardness, adhesion, and tribological performance. Beyond HVOF, alternative techniques such as directed energy deposition (Cho & Park, 2026) and laser cladding of carbide-reinforced composite coatings (Liu et al., 2022) have been explored for similar wear-resistance applications, while the influence of alloying elements such as Nb and Mo on the high-temperature wear behavior of HVOF-sprayed high-entropy alloy coatings has also been reported (Rymer et al., 2023).

Therefore, the present study aims to comparatively evaluate five metal-ceramic coating systems deposited by HVOF under identical processing conditions onto 65G steel. By analyzing the effects of spraying parameters on coating microstructure, hardness, roughness, and adhesive strength, this work seeks to determine the optimal technological regime and identify the coating composition that provides the best balance of mechanical and tribological properties for industrial applications.

MATERIALS AND METHODS

The study focused on the metal-ceramic coatings WC-Co-Cr, WC-NiCr, WC-Ni, Al_2O_3 -NiCr, and Cr_3C_2 -NiCr deposited on a 65G steel substrate. The chemical composition of the substrate and the powders used is presented in Tables 1.1 and 1.2, respectively.

Table 1.1. Chemical composition of the substrate material

65G steel								
Fe	C	Mn	Si	Ni	Cr	Cu	S	P
~97%	0.65–0.7%	0.9–1.2%	0.17–0.37%	Up to 0.25%	Up to 0.25%	Up to 0.2%	No more than 0.035%	No more than 0.035%
<i>Note – compiled by the authors</i>								

Table 1.2. Chemical composition of powders

WC-Co-Cr			
W	C	Co	Cr
Base	5.3%	10.0%	4.0%
WC-NiCr			
W	C	Ni	Cr
Base	5%	6%	8%

End of Table 1.2

WC-Ni			
W	C	Ni	
Base	5%	10%	
Al ₂ O ₃ -NiCr			
Al ₂ O ₃	Ni	Cr	
Base	6.2%	8.3%	
Cr ₃ C ₂ -NiCr			
Cr	C	Ni	Cr
Base	9.2%	12%	4.5%
Note – compiled by the authors			

Flame and high-velocity oxygen-fuel (HVOF) coating deposition was performed on an LH-5000 system manufactured by Zhengzhou Lijia Thermal Spray Machinery Co., Ltd. (Zhengzhou, China); all coatings from the powders under study were obtained in an atmospheric environment under a single spraying process, the parameters of which are given in Table 2.

Table 2. Spray parameters for WC-NiCr, WC-Ni, WC-Co-Cr, Cr₃C₂-NiCr, and Al₂O₃-NiCr coatings using the HVOF method

Parameter settings on the gas control panel	Pressure
Propane	2.9 bar
Oxygen	5 bar
Compressed air	3.2 bar
Spray distance	200 mm
Note – compiled by the author based on(Pawlowski, 2008)	

The powder feed rate was maintained constant at the manufacturer's standard operating setting for the LH-5000 system for all powders and was not logged as a separate numerical parameter during this experimental campaign; quantitative monitoring of the feed rate is planned for future studies to further support reproducibility.

The morphology and microstructure of the cross-sections of the sputtered coatings were examined using scanning electron microscopy (SEM) with a TESCAN VEGA4 LMH microscope (TESCAN, Brno, Czech Republic); The samples underwent standard metallographic preparation (embedding, grinding, polishing), and the elemental composition and distribution of components were determined by energy-dispersive spectroscopy (EDS). Tribological tests were conducted on an Anton Paar TRb3 tribometer (Anton Paar, Buchs, Switzerland) using a ball-on-disk setup according to ASTM G133-95 and ASTM G99, under dry friction conditions at room temperature without lubrication; the counterbody was a 100Cr6 steel ball of 6 mm radius, the applied load was 6 N, the sliding speed was 3 cm/s, the wear track radius was 3 mm, and the total sliding distance was 60 m, with continuous recording of the coefficient of friction; wear was evaluated based on friction track parameters with calculation of the volumetric wear rate. The adhesive and cohesive strength of the coatings was determined by scratch testing on a CSM Revetest RST scratch tester equipped with a Rockwell diamond indenter (120° cone angle, 200 μm tip radius) in accordance with ASTM C1624, applying a progressively increasing normal load from 1 N to 100 N at a loading rate of 100 N/min and an indenter travel speed of 10 mm/min, with recording

of the critical failure load. Microhardness was measured using the Vickers method on a Metolab 502 microhardness tester (Metolab, Russia) at a load of 100 g and a dwell time of 10 s across the cross-section of the coatings (at least six measurements for each type), while surface roughness was determined using a Model 130 profilometer (OJSC "PROTON Plant," Moscow, Russia) based on the results of five measurements with calculation of the Ra and Rz parameters.

RESULTS AND DISCUSSION

To evaluate the quality, structure, and thickness of the coatings applied by the HVOF method (conditions in Table 3.3), cross-sections were analyzed using scanning electron microscopy (Figure 1).

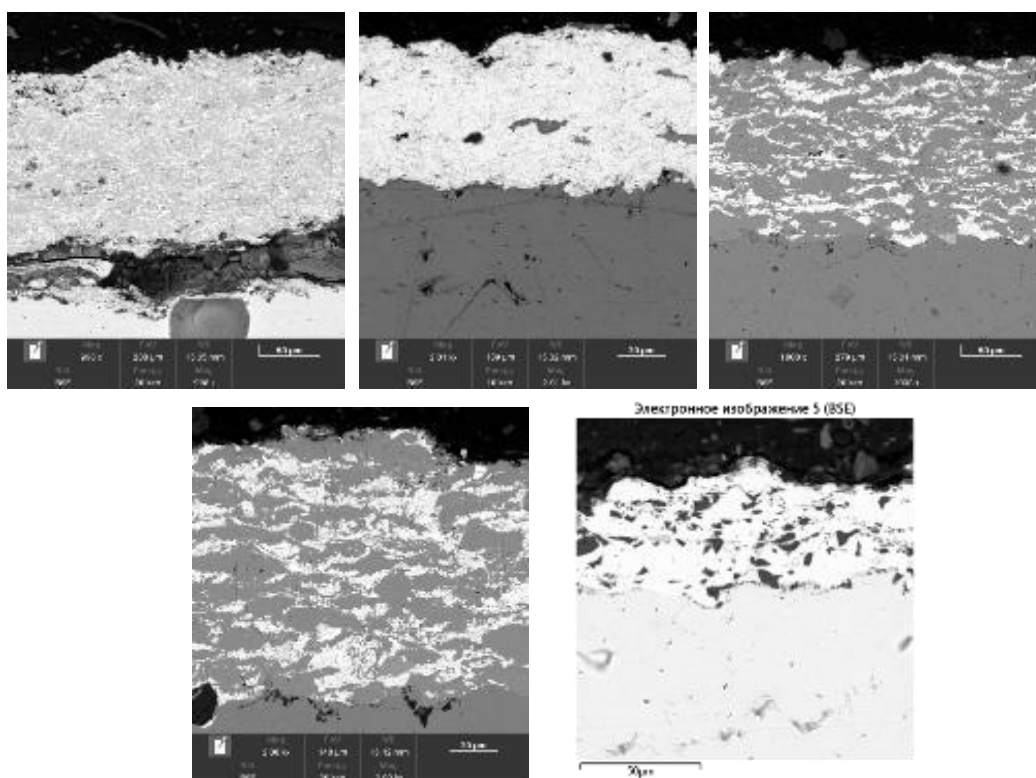


Figure 1. Cross-sections of WC-NiCr, WC-Ni, WC-Co-Cr, Al₂O₃-NiCr, and Cr₃C₂-NiCr coatings

Note – compiled by the authors

A comparative analysis of powder compositions showed that the nature of microstructure formation and the quality of the coatings depend significantly on the type of starting powder and the nature of the binder. Homogeneous WC-Co-Cr powder forms the densest and structurally most coherent lamellar structure with a uniform distribution of the WC carbide phase in the Co-Cr metal matrix, as confirmed by SEM and EDA mapping data, consistent with the dense lamellar morphology reported for WC-Co-Cr coatings by Książek et al. (2021). In contrast, the WC-Ni and WC-NiCr composite powders, which are mechanical mixtures of components, form a pronounced heterogeneous layered structure: the ductile binder (Ni or NiCr) deforms under high-speed impact and envelops the hard WC particles; however, complete mutual melting and phase diffusion do not occur, leading to a non-uniform distribution of elements. The Cr₃C₂-NiCr coating demonstrated critically low adhesion strength and complete delamination from the substrate, despite its relatively large thickness (144 μm), indicating insufficient interphase

bonding under the selected HVOF conditions, a failure mode consistent with the reduced adhesive strength of Cr_3C_2 -NiCr coatings reported by Ksiazek and Boron (2025) and by Daniel et al. (2020). The most unstable layer formation was observed for Al_2O_3 -NiCr: due to the low plasticity of the Al_2O_3 ceramic phase and its weak fixation upon impact, the coating turned out to be depleted in ceramic and enriched in metallic binder, which led to a minimal thickness ($55\text{ }\mu\text{m}$) and a disruption of the initial phase composition, in line with the lower structural stability of oxide-based systems noted by Bochenek et al. (2022) when comparing HVOF, plasma spraying, and laser cladding of Al_2O_3 -containing coatings. Thus, powders with a homogeneous structure ensure a more uniform phase distribution and better structural integrity of the coating, whereas mechanical mixtures and systems with a high proportion of brittle ceramics exhibit an increased tendency toward heterogeneity and defects during spraying.

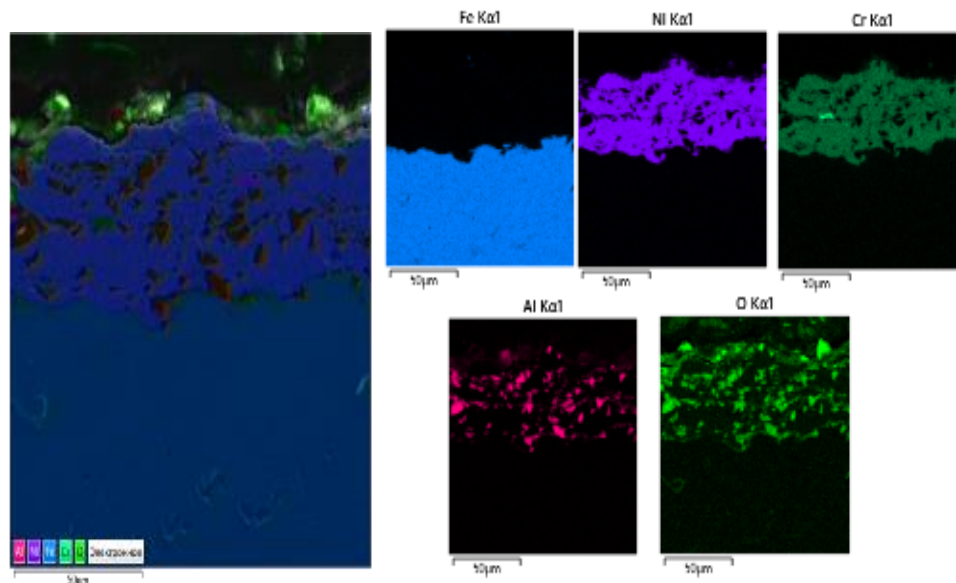


Figure 2.1. SEM image of Al_2O_3 -NiCr

Note – compiled by the authors

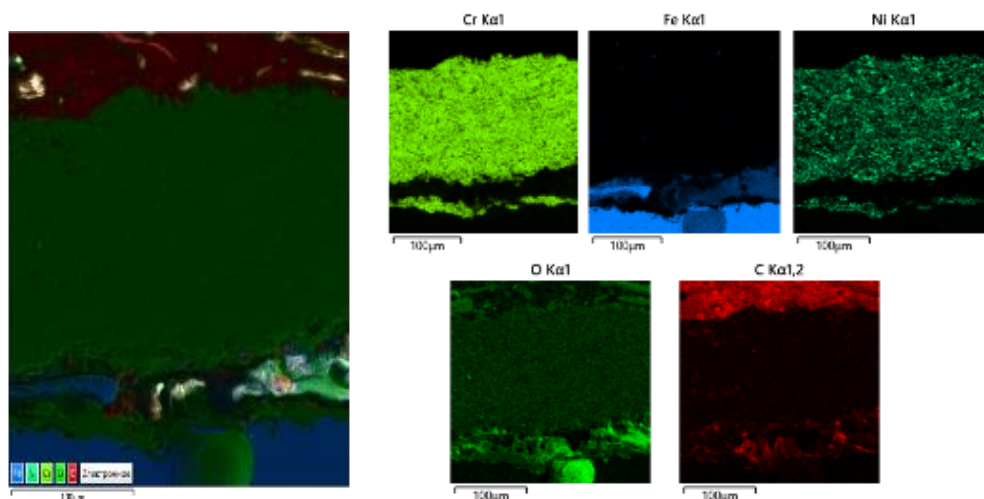


Figure 2.2. SEM image of Cr_3C_2 -NiCr

Note – compiled by the authors

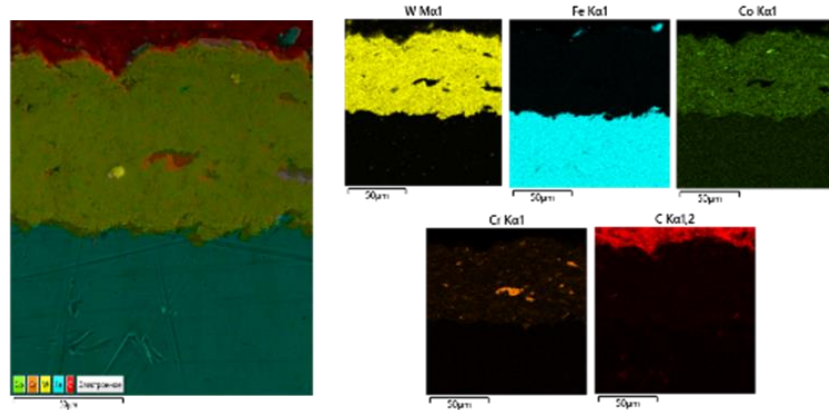


Figure 2.3. SEM image of WC-Co-Cr

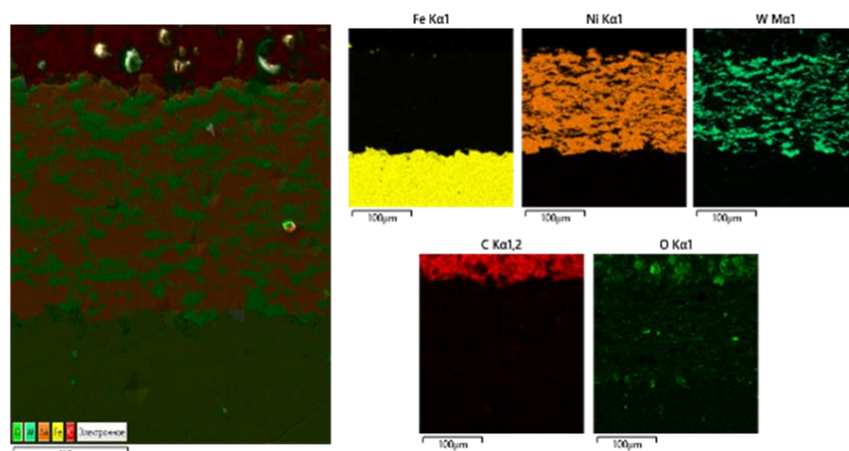


Figure 2.4. SEM image of WC-Ni

Note – compiled by the authors

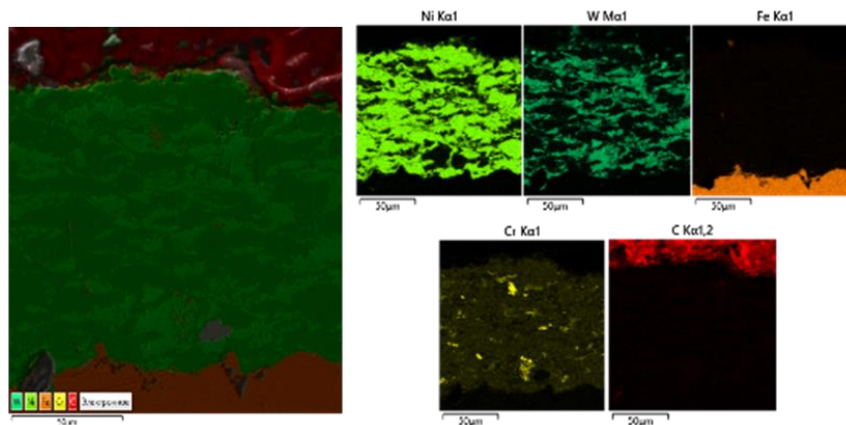


Figure 2.5. SEM image of WC-NiCr

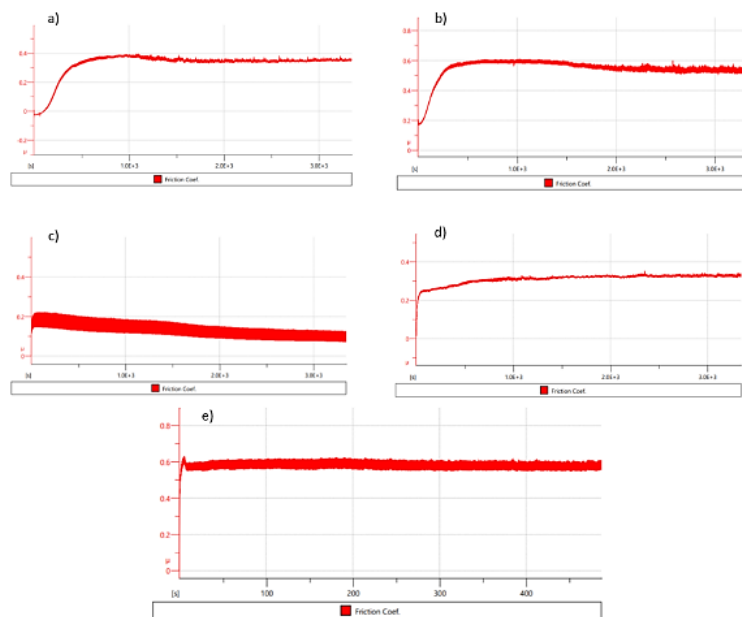
Note – compiled by the authors

Tribological tests were conducted to evaluate the operational properties of the coatings, determine their wear resistance, and assess their resistance to friction under conditions of surface contact. The primary focus was on analyzing the coefficient of friction of coatings applied using the HVOF method, which allows for determining the influence of the spraying technology on the tribological characteristics of the tested samples.

Table 3. Coefficient of friction values for HVOF-applied coatings

Powder	Coefficient of friction
WC-NiCr	0.326
WC-Ni	0.545
WC-Co-Cr	0.143
Cr ₃ C ₂ -NiCr	0.310
Al ₂ O ₃ -NiCr	0.630
<i>Note – compiled by the authors</i>	

Analysis of the coefficient of friction for coatings applied by the HVOF method (Figure 3, Table 3) revealed significant differences in their tribological characteristics. The lowest coefficient of friction was recorded for the WC-Co-Cr coating ($\mu = 0.143$), indicating the formation of a stable contact layer and the predominance of a moderate abrasive-adhesive wear mechanism, in agreement with the low-friction behavior reported for WC-Co-Cr coatings by Nie et al. (2024) and Shu et al. (2022). The WC-NiCr ($\mu = 0.326$) and Cr₃C₂-NiCr ($\mu = 0.310$) coatings are characterized by similar friction coefficients and a stable steady-state regime after the running-in stage, indicating a balanced combination of the hard carbide phase and the metallic matrix. For the WC-Ni coating ($\mu = 0.545$), a higher friction level is observed, caused by an increased adhesive component due to the nickel matrix, consistent with the binder-controlled friction behavior described for WC-Ni coatings by Qiao et al. (2024). The highest coefficient of friction was found for the Al₂O₃-NiCr coating ($\mu = 0.630$), which is associated with a pronounced abrasive interaction mechanism due to the high hardness of the oxide phase, corroborating the comparatively poor tribological performance of oxide-reinforced HVOF coatings reported by Bochenek et al. (2022). In general, carbide coatings exhibit lower tribological properties compared to the oxide coating, with the best anti-friction properties observed in the WC-Co-Cr system.

**Figure 3.** Graph of the coefficient of friction for WC-NiCr(a), WC-Co-Cr(c), WC-Ni(b), Cr₃C₂-NiCr(d), Al₂O₃-NiCr(e)

Note – compiled by the authors

Based on the results of scratch tests performed on the RST300 system, coatings (a–e) demonstrate varying resistance to progressively increasing load, which is reflected in the nature of changes in friction force, coefficient of friction, penetration depth, and acoustic emission signal. The most stable behavior is observed in sample (c), which is characterized by minimal fluctuations in the coefficient of friction, a smoother increase in penetration depth, and the absence of pronounced acoustic emission spikes even at high loads, indicating high cohesive strength and adhesive durability, in agreement with the high scratch resistance reported for cobalt-modified carbide coatings by Ksiazek and Łyp-Wrońska (2024). Sample (b) demonstrates similar performance; however, under increased loads, local AE peaks are recorded, indicating the onset of microcrack formation. Sample (e) is characterized by intermediate durability: isolated signal spikes and a more noticeable increase in residual depth are observed. For coatings (a) and especially (d), early acoustic emission peaks and sharp fluctuations in friction force are recorded, indicating an earlier onset of critical loads (L_{C1} – L_{C2}) and lower adhesive strength compared to the other samples, a pattern similarly observed for Cr_3C_2 -based HVOF coatings under impact and scratch loading by Daniel et al. (2020). For the Cr_3C_2 -NiCr coating (d), which showed the earliest and most pronounced failure, four replicate scratch tests were performed to quantify the critical load; the first cohesive cracks were consistently detected at 35–38 N, giving an average critical load of $L_{C1} = 37.0$ N, confirming the markedly lower adhesive/cohesive strength of this system relative to the other four coatings. For the remaining coatings (a, b, c, e), the critical loads L_{C1} and L_{C2} were identified qualitatively from the combined analysis of the acoustic emission signal, friction force, and penetration depth curves, correlated with optical and SEM examination of the scratch tracks, since this approach was sufficient to reliably rank the relative adhesive and cohesive performance of the five coating systems within the scope of the present comparative study; quantitative determination of L_{C1} and L_{C2} for all five coatings is planned as part of a follow-up study. Thus, based on the set of scratch test parameters, the relative durability of the coatings can be ranked in descending order: (c) $\approx$ (b) > (e) > (a) > (d).

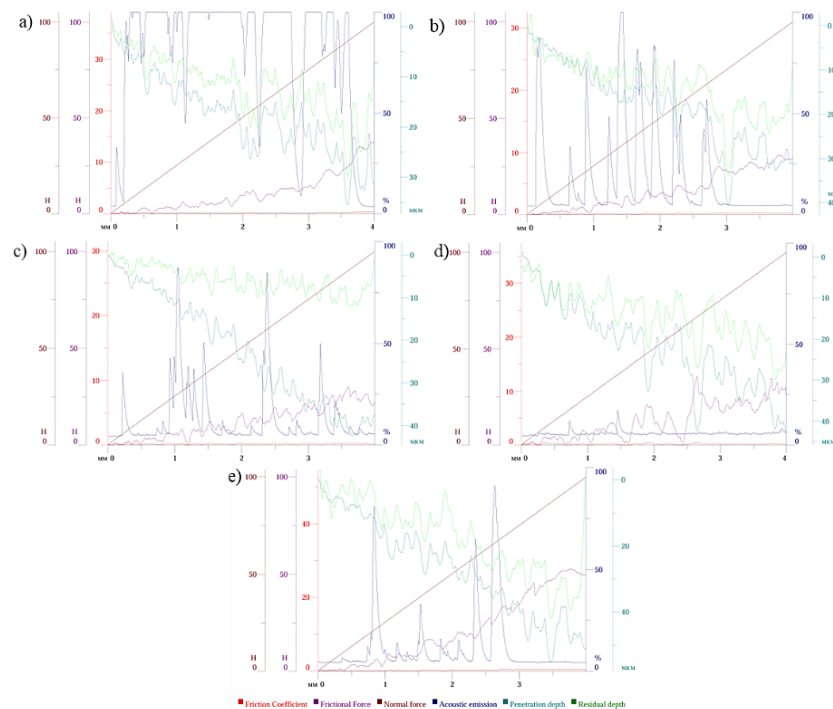


Figure 4.1. Scratch test graph

Note – compiled by the authors

Analysis of optical images of the scratch tracks confirms the tribometric data obtained. Samples (c) and (b) are characterized by a smooth, narrow scratch with minimal chipping at the edges, indicating a predominance of plastic deformation without intense delamination. Sample (e) exhibits localized chipping and partial failure along the track edges, which corresponds to intermediate adhesive strength. In coatings (a) and especially (d), pronounced areas of chipping, uneven edges, and track widening are observed with increasing load, indicating the development of cohesive cracks and partial delamination of the coating from the substrate. The morphology of the tracks correlates with the recorded acoustic emission peaks and the increase in residual penetration depth, confirming differences in the mechanism and intensity of failure of the studied coatings, consistent with the microstructure-dependent failure transitions described for cold- and HVOF-sprayed carbide coatings by Trelka-Druzic et al. (2024).

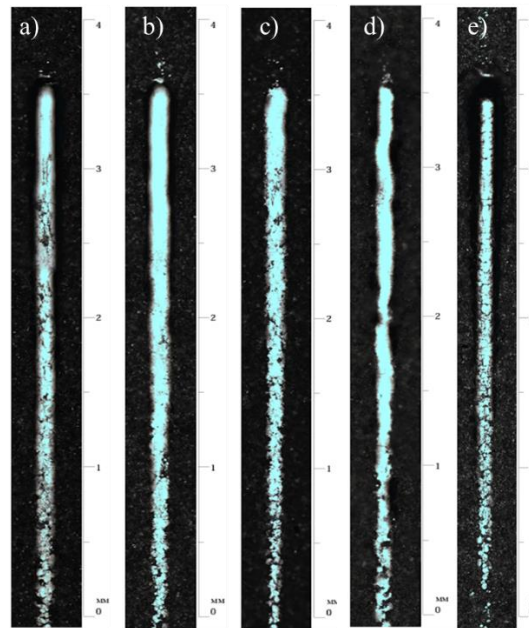


Figure 4.2. Panoramic image of scratch testing

Note – compiled by the authors

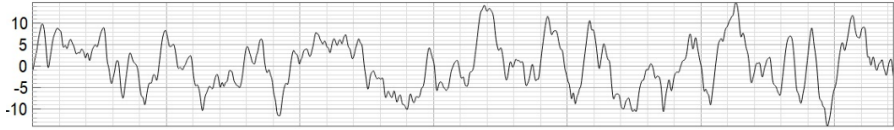
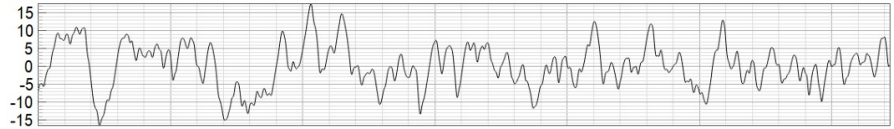
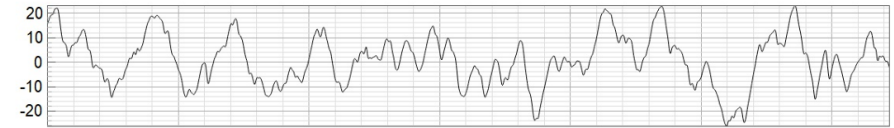
The results of the coating hardness measurements are presented in Table 3.5 and demonstrate the dependence of mechanical properties on the chemical composition of the powder material used in HVOF coating application. Analysis of the data shows that the highest microhardness is observed in the WC–Co–Cr coating and amounts to 1316.87 HV, which is associated with the presence of a carbide phase and a cobalt-chromium binder matrix in the composition, ensuring high strength and structural stability; comparable hardness levels for WC–Co–Cr coatings have been reported by Nie et al. (2024) and Shu et al. (2022). Slightly lower hardness values were recorded for the Cr₃C₂–NiCr (1088.6 HV) and WC–NiCr (785.2 HV) coatings, which is explained by the distribution characteristics of carbide particles in the nickel-chromium matrix, consistent with the porosity- and carbide-dissolution-driven hardness trends summarized for Cr₃C₂–NiCr coatings by Seitov et al. (2025). The WC–Ni coatings exhibited a hardness of 721.2 HV, whereas the minimum hardness value of 631.59 HV was obtained for the Al₂O₃–NiCr coating, which may be attributed to the ceramic nature of the oxide phase and the lower density of structural defects formed during the spraying process. Overall, the results obtained indicate a significant influence of the powder material composition on the formation of the mechanical properties of the coatings.

Table 4. Coating Hardness

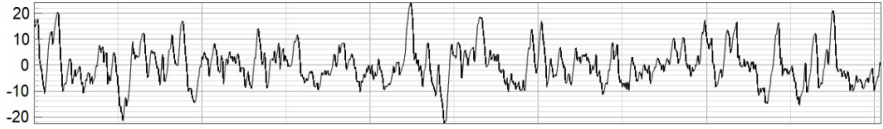
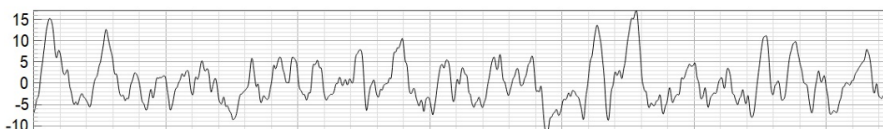
Powder	Hardness
WC-Co-Cr	1316.87
Cr ₃ C ₂ - NiCr	1088.6
Al ₂ O ₃ - NiCr	631.59
WC - NiCr	785.2
WC - Ni	721.2
<i>Note – compiled by the authors</i>	

The results of surface roughness measurements indicate differences in the microgeometry of the formed layers depending on the HVOF spraying conditions. Among the samples studied, the lowest surface roughness value is observed in sample No. 5 and amounts to $R_a = 3.881 \mu\text{m}$, indicating more uniform coating formation and a reduction in surface defects. The maximum roughness was recorded for sample No. 3 and is equal to $R_a = 8.130 \mu\text{m}$. Since all five coatings were deposited under identical HVOF spraying parameters (Table 2), the observed differences in roughness cannot be attributed to variations in the spraying regime itself; instead, they are considered to primarily reflect the influence of powder composition and the behavior of the individual particles during impact and solidification. The high roughness of sample No. 3 (Al₂O₃-NiCr) is consistent with the poor fixation and fragmentation of the brittle Al₂O₃ ceramic phase upon high-velocity impact discussed above, which promotes a more irregular surface relief, in agreement with the dependence of surface topography on particle behavior during HVOF spraying reported by Wang, R. et al. (2026). Samples No. 1, No. 2, and No. 4 exhibit intermediate roughness values— $4.709 \mu\text{m}$, $4.691 \mu\text{m}$, and $5.614 \mu\text{m}$, respectively, which indicates a comparatively uniform particle deposition behavior for these compositions under the applied HVOF regime. Overall, since the spraying process parameters were held constant, the results obtained show that the composition of the powder and the resulting particle deposition and solidification behavior have a significant influence on the formation of the surface relief and the quality of the coatings.

Table 5. Surface roughness of coatings

No.	Ra	Roughness graph
1	4.709	
2	4.691	
3	8,130	

End of Table 5

4	5,614	
5	3,881	
Note – compiled by the authors		

CONCLUSION

Studies of WC–Co–Cr, WC–NiCr, WC–Ni, Cr₃C₂–NiCr, and Al₂O₃–NiCr coatings produced by the HVOF method have shown that their structure and performance properties depend significantly on the composition of the powder mixture and the nature of the binder phase: microstructural analysis revealed the formation of the densest, most uniform, and structurally intact lamellar structure in the WC–Co–Cr coating, whereas the WC–Ni and WC–NiCr systems are characterized by greater heterogeneity, Cr₃C₂–NiCr by reduced adhesion and a tendency to delamination, and Al₂O₃–NiCr by instability in layer formation; tribological tests showed the lowest coefficient of friction for WC–Co–Cr ($\mu = 0.143$), intermediate values for Cr₃C₂–NiCr (0.310) and WC–NiCr (0.326), an elevated coefficient for WC–Ni (0.545), and the highest for Al₂O₃–NiCr (0.630), confirming the superiority of carbide systems in terms of anti-friction characteristics; scratch test results demonstrated the highest adhesive and cohesive strength in WC–Co–Cr, similar values in WC–Ni, average durability in Al₂O₃–NiCr, and the earliest failure in WC–NiCr and especially Cr₃C₂–NiCr; microhardness measurements showed the maximum value for WC–Co–Cr (1316.87 HV), high values for Cr₃C₂–NiCr (1088.6 HV), average values for WC–NiCr (785.2 HV) and WC–Ni (721.2 HV), and the lowest value for Al₂O₃–NiCr (631.59 HV); roughness analysis confirmed the influence of HVOF process parameters on the surface microtopography (Ra in the range of 3.881–8.130 μm). Taken together, the results indicate that the WC–Co–Cr coating provides the best balance of microstructural integrity, hardness, adhesive strength, and tribological properties and is the most promising for use under conditions of severe wear, a conclusion in line with the strong cavitation and scratch performance reported for WC–Co–Cr-based HVOF coatings in structural steel applications by Kumar et al. (2026) and Li et al. (2024).

CONFLICT OF INTEREST: The authors declare that there is no conflict of interest.

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Information about authors



Arystanbek Kussainov – PhD doctoral student in Technical Physics, East Kazakhstan Technical University named after D. Serikbaev, Ust-Kamenogorsk, Kazakhstan,
e-mail: arys20055@gmail.com,
ORCID: <https://orcid.org/0000-0003-4623-4681>,



Molbossynov Ermakhan Serikuly – Bachelor of Electrical Power Engineering, Research Scientist at the Scientific Center for «Protective and Functional Coatings», East Kazakhstan Technical University named after D. Serikbaev, Ust-Kamenogorsk, Kazakhstan,
e-mail: mr.molbosunov@gmail.com ,
ORCID: <https://orcid.org/0009-0009-0578-6544> ,



Magazov Nurtoleu – Researcher, Scientific Center “Protective and Functional Coatings”, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan,
e-mail: magazovn@gmail.com,
ORCID: <https://orcid.org/0000-0002-9941-9199>



Abizhanova Indira Kenzhebekovna – doctoral student of the specialty "Metallurgy", Research Scientist at the Scientific Center for «Protective and Functional Coatings», East Kazakhstan Technical University named after D. Serikbaev, Ust-Kamenogorsk, Kazakhstan,
e-mail: iabizhanova@gmail.com ,
ORCID: <https://orcid.org/0009-0006-3218-7246>



Kuanyshbay Rashid – Master's student in Technical Physics, D.Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan,
e-mail: rashidmaratly08@gmail.com,
ORCID: <https://orcid.org/0009-0009-7661-2605>



Alimov Abai Urustembaevich – Bachelor's degree in “Technical Physics”. D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan,
e-mail: abai.alimov4421@gmail.com
ORCID: <https://orcid.org/0009-0007-6968-3160>
