

INVESTIGATION OF THE FORMATION OF STRUCTURE WEAR-RESISTANT PROPERTIES OF WC-CO-CR COATINGS PRODUCED BY HVOF AND DETONATION SPRAYING

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ABSTRACT

WC-Co-Cr cermet coatings are widely used to improve the wear resistance and service life of machine components operating under abrasive and sliding contact conditions. The present study aims to comparatively evaluate the structural, mechanical, and tribological characteristics of WC-Co-Cr coatings deposited on structural steel 20GL using detonation spraying (DS) and High Velocity Oxy-Fuel (HVOF) spraying. A homogeneous fully fused WC-Co-Cr powder with a particle size of 20–40 μm was used. The morphology and composition of the powder and coatings were examined by scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS). Microhardness was measured using a FISCHERSCOPE HM 2000 system, while tribological behavior was evaluated under dry sliding conditions using a ball-on-disc tribometer. The DS coating exhibited higher microhardness of 1449 ± 52 HV compared with 1317 ± 48 HV for HVOF ($p < 0.001$). In contrast, the HVOF coating demonstrated superior tribological performance, with a friction coefficient of 0.143 ± 0.012 compared with 0.545 ± 0.018 for DS, and a wear rate approximately three times lower. The scientific novelty lies in the simultaneous comparative assessment of powder morphology, coating microstructure, elemental composition, microhardness, and tribological behavior on 20GL steel under identical test conditions. The results provide a practical basis for selecting the appropriate spraying technology according to the dominant wear mechanism: DS for abrasive loading and HVOF for sliding friction conditions.

INTRODUCTION

Machine parts operating under conditions of intense friction, abrasive action, and cyclic loading undergo accelerated wear of the surface layer, leading to premature failure of assemblies and significant economic losses. Despite the widespread use of various surface hardening methods, the problem of ensuring component durability under high contact loads remains relevant. One promising solution is the application of WC-Co-Cr cermet coatings by thermal spraying methods, which allow extending the service life of parts without changing the base material (Rakhadilov, Muktanova and Zhurerova, 2023).



A homogeneous fully fused WC–Co–Cr powder was used as the spray material. Among thermal spray technologies for WC–Co–Cr-based coatings, three methods are most widely used: air plasma spraying (APS), detonation spraying (DS), and High Velocity Oxy-Fuel spraying (HVOF) (Yu *et al.*, 2022). Each method is characterized by a different ratio of thermal and kinetic energy transferred to the powder particles, which directly determines the microstructure and properties of the resulting coatings.

The air plasma method is characterized by a very high jet temperature (up to 10,000 °C and above). Under such conditions, WC particles are subjected to intense thermal exposure, which leads to degradation of the mechanical and tribological properties of the coating (Yuan *et al.*, 2013). In contrast to the plasma method, detonation and HVOF spraying are characterized by more moderate thermal exposure at significantly higher particle velocities, where high kinetic energy is the determining factor (Sadeghimeresht, Markocsan and Nylén, 2017).

The HVOF spraying method enables the formation of coatings with high density and cohesive strength due to supersonic particle velocities (600–900 m/s) (Zhao *et al.*, 2016). Intense plastic deformation of particles upon impact with the substrate leads to the formation of a characteristic lamellar structure with high interlayer cohesion. It is precisely this microstructural feature that determines the stable tribological behavior of HVOF coatings: the developed lamellar boundaries impede crack propagation and ensure uniform contact interaction under sliding friction (Méndez-Medrano *et al.*, 2018).

Detonation spraying, owing to its pulsed nature and ultra-high particle kinetic energy, allows achieving maximum microhardness values. The physical hardening mechanism in detonation spraying is associated with the high pressure in the detonation wave, which provides particle velocities of up to 800 m/s and their intense plastic deformation upon impact. This leads to the formation of an ultra-dense structure with high dislocation density and residual compressive stresses, which together determine the increased resistance to plastic deformation and high coating hardness (Ulyanitsky, V.Y.*et al.*, 2025).

Analysis of published work reveals several unresolved issues. Most comparative studies of HVOF and DS WC–Co–Cr coatings do not account for the morphology of the starting powder as an independent variable, although it determines the homogeneity of structure and stability of coating properties: spherical fully fused powders provide substantially more uniform feed and melting compared to mechanically crushed powders (Kumar, Chittosiya and Shukla, 2018). Furthermore, existing comparative studies have been performed predominantly on stainless or high-alloy steel substrates, whereas low-alloy structural steels widely used in Kazakhstani machine-building industry in particular, steel 20GL remain insufficiently studied. Finally, no prior work has simultaneously provided a comprehensive assessment of powder morphology, microstructure, elemental composition (EDS), microhardness, and tribological characteristics under identical test conditions, which has prevented establishing a quantitative relationship between structural features and operational properties of coatings.

The scientific novelty of this work is as follows. Most published comparative studies of HVOF and DS WC–Co–Cr coatings have been performed on stainless or high-alloy steel substrates (Méndez-Medrano *et al.*, 2018) (Kumar, Chittosiya and Shukla, 2018), without statistical data processing and without simultaneous comprehensive assessment of all key characteristics under identical test conditions. The present work is the first to conduct such a study on structural steel 20GL, widely used in Kazakhstani machine-building, using a homogeneous fully fused WC–Co–Cr powder on a CCDS2000 system, including simultaneous assessment of powder morphology, cross-section microstructure, elemental composition (EDS analysis), microhardness ($n = 9$, $P = 0.95$), and tribological characteristics including SEM analysis of wear tracks. It is established that the spraying method determines the balance between hardness (DS: 1449 ± 52 HV) and tribological characteristics (HVOF: $\text{CoF} = 0.143 \pm 0.012$, $K_w = (1.2 \pm 0.2) \times 10^{-6}$

mm³/(N·m), $P = 0.95$), enabling informed selection of technology based on the dominant wear mechanism in specific service conditions.

The objective of the present work is a comparative evaluation of microhardness and tribological characteristics of WC–Co–Cr coatings deposited on steel 20GL by DS and HVOF methods, based on analysis of microstructure and elemental composition, to establish the relationship between coating structure and operational properties.

MATERIALS AND METHODS

A low-alloy low-carbon steel grade 20GL was used as the substrate. Three samples were prepared for each spraying method (6 samples total). Prior to coating deposition, the sample surfaces were carefully prepared. The first stage involved grinding with P250 abrasive paper to remove oxide films and contaminants. Subsequently, grit blasting with electrocorundum grades 14AF180, 25AF220, 14AF70, 14AF24, 25AF24 was performed under the following parameters: compressed air working pressure 0.7 MPa; nozzle-to-surface distance 100–120 mm; treatment angle 75–90°. The treatment provided surface roughness $R_a = 6\text{--}8\text{ }\mu\text{m}$, necessary to ensure coating adhesion to the substrate. The chemical composition of steel 20GL is given in Table 1.

Table 1. Chemical composition of steel 20GL

Element	Symbol	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
Chromium	Cr	–
Nickel	Ni	–
Copper	Cu	–
Sulphur	S	up to 0.040
Phosphorus	P	up to 0.040
Iron	Fe	~97

Note – compiled by the authors based on GOST 977-88 and GOST 1050-2013

A commercial fully fused (homogeneous) WC–Co–Cr cermet powder (commercial supplier, China) was used as the spray material. To eliminate the influence of particle size on kinetics in the supersonic jet and ensure high experimental reproducibility, a strictly isolated powder fraction with particle size range of 20-40 μm (median diameter $D_{50} = 28\text{ }\mu\text{m}$) was used. The powder composition is given in Table 2.

Table 2. Chemical composition of WC–Co–Cr powder

WC-Co-Cr			
W	C	Co	Cr
Base	5.3%	10.0%	4.0%

Note – compiled by the authors based on powder manufacturer data

Coatings were deposited by two thermal spray methods (M. Skakov *et al.*, 2023): detonation spraying and High Velocity Oxy-Fuel (HVOF) spraying.

DS coatings were produced on a CCDS2000 detonation spraying unit (LIH SB RAS, Novosibirsk, Russia) (Fig. 1) controlled by a computer system. Main process parameters: working gases – C_2H_2 , O_2 , N_2 ; detonation cycle frequency – 4 Hz; barrel fill fraction with combustible mixture – 50%; gas ratio $\text{C}_2\text{H}_2:\text{O}_2:\text{N}_2$ – 1:1.1:0.5 (vol.); spraying distance – 200 mm; particle velocity in flight – 600–800 m/s; particle temperature in flight – 2200–2600 °C (Ulyanitsky, V.Y.*et al.*, 2025).

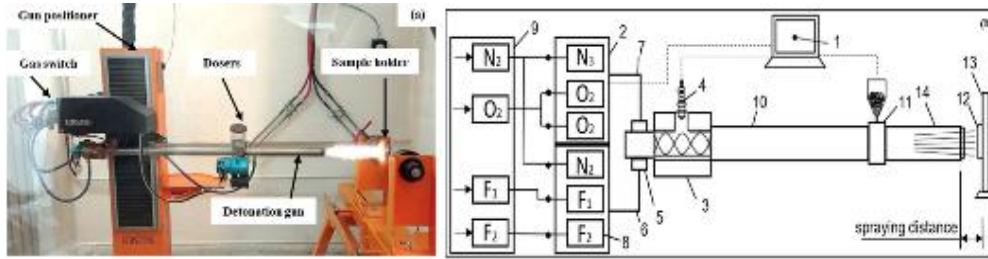


Figure 1. General view of the CCDS200 installation (a) and its technological diagram (b):

1-control panel, 2-gas distributor, 3-ignition chamber, 4-spark plug, 5-barrel valve, 6-fuel line, 7-oxygen line, 8-gas valves, 9-gas supply unit, 10-barrel stone part, 11-powder feeder (dispenser), 12-workpiece; 13-manipulator, 14-barrel muzzle part

Note – schematic and spraying process according to GOST R 9.316-2006 "Thermal spray coatings. General requirements and inspection methods"

HVOF coatings were deposited using a High Velocity Oxy-Fuel (HVOF) spraying unit (Fig. 2) to form dense coatings with high hardness and wear resistance (Donadei *et al.*, 2020). Fuel: propane (C_3H_8); oxidizer: oxygen (O_2); carrier gas: compressed air. Spraying parameters are given in Table 3. Spraying distance was 200 mm. WC-Co-Cr powder is introduced into the jet, heated and accelerated to optimal temperature and velocity, ensuring its deformation and dense bonding to the substrate without complete melting.

Table 3. HVOF spraying parameters

Gas	Pressure (bar)	Flow rate (L/min)
Propane (C_3H_8)	2.9	55–60
Oxygen (O_2)	5.0	220–230
Compressed air	3.2	400–420

Note – compiled by the authors

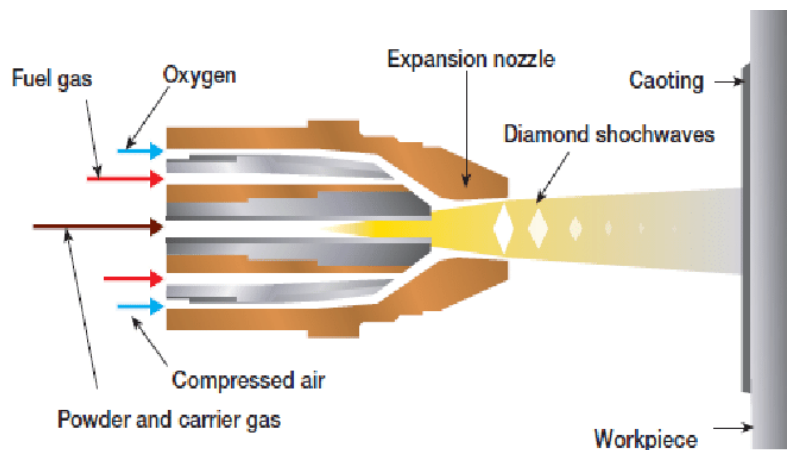


Figure 2. General block diagram of HVOF

Note – the installation diagram and HVOF spraying process are given in (An Introduction to Thermal Spray. – International Thermal Spray Association, 2015)

Morphological characteristics of powder particles, as well as the surface and cross-section of coatings, were characterized by scanning electron microscopy (SEM) using a TESCAN

VEGA4 LMH (TESCAN, Brno, Czech Republic); energy-dispersive spectroscopy (EDS) analysis was performed on an Xplore 30 system (Oxford Instruments, Oxford, UK).

Microhardness and elastic modulus of the coatings were measured using a FISCHERSCOPE HM 2000 system (Helmut Fischer GmbH, Sindelfingen, Germany) operated with WIN-HCU software version 7.1. This instrument is designed to evaluate microhardness and other mechanical properties of materials in accordance with ISO 14577 on cross-sections of samples. In all nine tests, dwell time was 10 s at a load of 300 mN. Statistical reliability was ensured by performing 9 consecutive tests ($n = 9$) for each technological regime.

Tribological studies were conducted on an Anton Paar TRb3 tribometer (Anton Paar, Buchs, Switzerland) in a ball-on-disc configuration in accordance with international standards ASTM G133-95 and ASTM G99. Testing was carried out under dry sliding conditions (without lubrication) at room temperature (22 ± 2 °C) and relative air humidity of $40 \pm 5\%$. A standardized bearing steel 100Cr6 ball of radius 6 mm was used as the counterbody. Tests were performed at the following fixed parameters: normal load - 6 N; linear sliding speed - 3 cm/s; wear track radius - 3 mm; total sliding distance - 60 m. To confirm reproducibility, at least 3 identical samples ($N = 3$) were tested for each coating type, and the mean friction coefficient (CoF) and wear rate (Kw) were determined from the results.

RESULTS AND DISCUSSION

The WC–Co–Cr cermet powder used for coating deposition was characterized by SEM (Fig. 3). Particles are predominantly spherical in shape, ensuring good flowability and uniform feed during spraying. The fully fused structure of the particles provides a uniform distribution of tungsten carbide (WC) in the Co–Cr metallic binder (M. K. Skakov *et al.*, 2023).

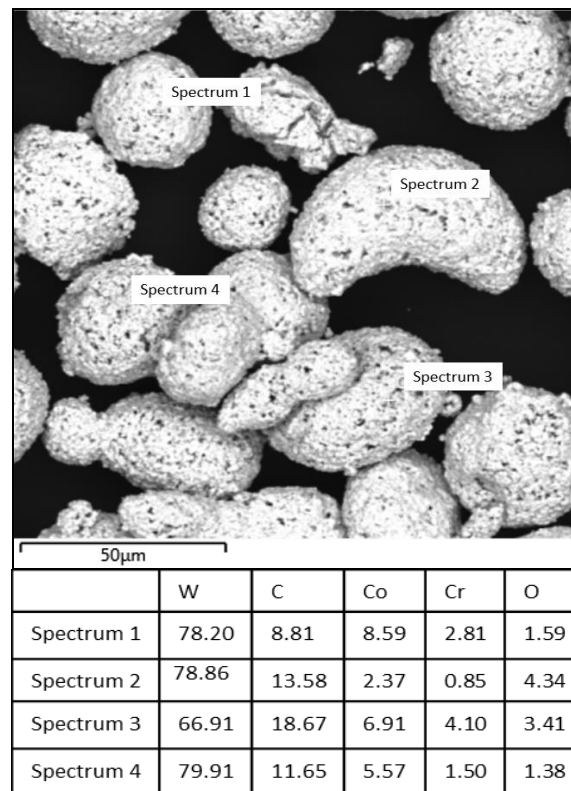


Figure 3. SEM image and EDS results of WC–Co–Cr powder

Note – compiled by the authors

Microstructural analysis of DS coatings revealed the formation of a dense lamellar structure with high adhesion to the substrate (Fig. 4). The thickness of the DS WC–Co–Cr coating, measured from cross-sectional SEM images, was $53 \pm 3 \mu\text{m}$ ($n = 3$). The structure is characterized by a minimum number of pores and virtually indistinguishable inter-lamellar boundaries, indicating effective densification under the impact of the detonation wave.

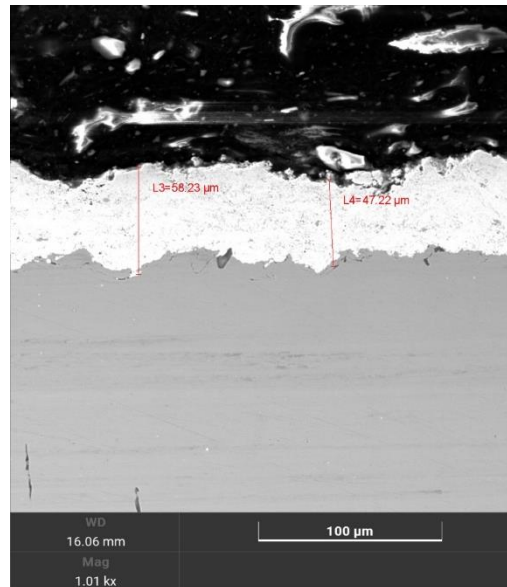


Figure 4. Cross-section of DS WC–Co–Cr coating

Note – compiled by the authors

EDS mapping of the DS coating cross-section (Fig. 5) confirmed uniform distribution of W, C, Co, and Cr elements throughout the coating thickness, consistent with the composition of the starting powder (Table 2).

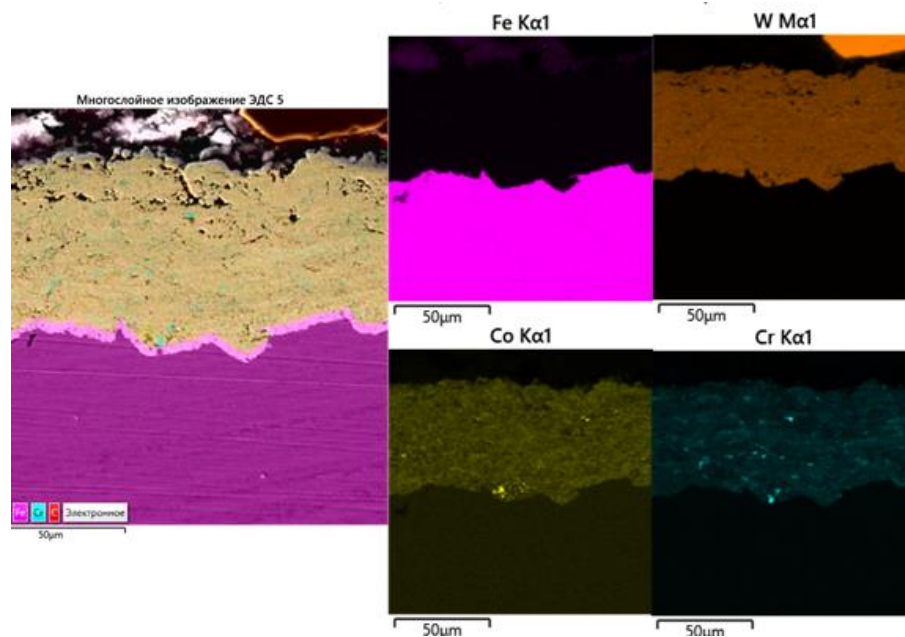


Figure 5. EDS mapping of DS WC–Co–Cr coating cross-section

Note – compiled by the authors

SEM microstructural analysis of the HVOF WC–Co–Cr coating cross-section (Fig. 6) showed the formation of a homogeneous dense layer uniformly distributed over the substrate surface. The thickness of the HVOF coating, based on three independent SEM measurements, was $70 \pm 4 \mu\text{m}$ ($n = 3$). The structure demonstrates high integrity and a near-complete absence of macro-defects, indicating effective cohesion of the WC hard phase with the Co–Cr matrix.

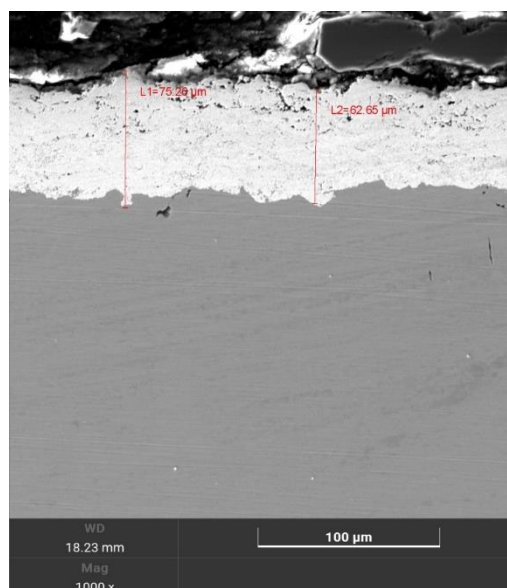


Figure 6. Cross-section of HVOF WC–Co–Cr coating

Note – compiled by the authors

EDS mapping of the HVOF coating cross-section (Fig. 7) showed the formation of a homogeneous dense structure with uniform distribution of the WC carbide phase in the Co–Cr metallic binder. The elemental composition of the coating according to EDS data corresponds to the composition of the starting powder (Table 2).

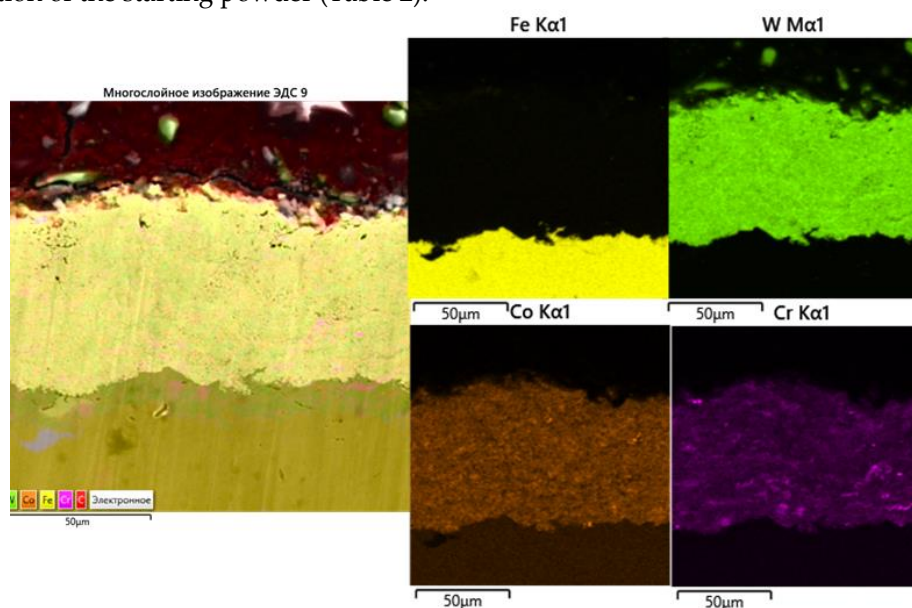


Figure 7. EDS mapping of HVOF WC–Co–Cr coating cross-section

Note – compiled by the authors

Comparative SEM analysis of cross-sections showed that both coatings have a dense, homogeneous structure with good adhesion to the 20GL steel substrate and no visible cracks or delamination. The DS coating ($53 \pm 3 \mu\text{m}$, $n = 3$) is characterized by a monolithic structure with virtually indistinguishable inter-lamellar boundaries and a minimum number of defects. The HVOF coating ($70 \pm 4 \mu\text{m}$, $n = 3$) also demonstrates high density but contains isolated dark inclusions identified as pores or oxide phases. EDS mapping confirmed uniform distribution of W, C, Co, and Cr throughout the thickness of both coatings, consistent with the nominal composition of the starting powder.

Microhardness was measured on cross-sections of each coating at a load of 300 mN and dwell time of 10 s ($n = 9$ tests for each method). Confidence intervals were calculated at $P = 0.95$. Results are given in Table 4.

Table 4. Microhardness of WC–Co–Cr coatings

Spraying method	Mean value (HV)	SD ($\pm$ HV)	Confidence interval ($P = 0.95$, $n = 9$)
DS	1449	52	1449 ± 52 HV
HVOF	1317	48	1317 ± 48 HV
<i>Note – compiled by the authors</i>			

The DS coating showed a mean microhardness of 1449 ± 52 HV ($P = 0.95$, $n = 9$), while the HVOF coating showed 1317 ± 48 HV ($P = 0.95$, $n = 9$). The difference is 132 HV ($\approx 10\%$) and is statistically significant: Student's t-test at $df = 16$ gives $t = 5.9 > t_{0.05} = 2.12$ ($p < 0.001$).

The higher hardness of the DS coating is caused by the pulsed nature of the process: the high pressure of the detonation wave provides intensive plastic deformation of particles upon impact, forming an ultra-dense structure with high dislocation density and compressive residual stresses (Ulyanitsky, V.Y.*et al.*, 2025). The slightly lower hardness of the HVOF coating is associated with the more moderate thermal and kinetic regime of the continuous spraying process.

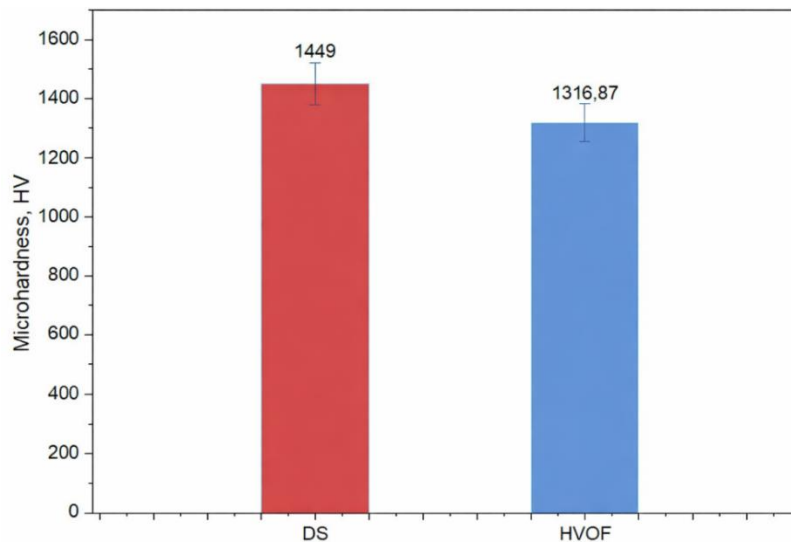


Figure 8. Microhardness comparison of DS and HVOF coatings

Note – compiled by the authors

Tribological tests were conducted in a ball-on-disc configuration under dry sliding conditions ($N = 3$ samples for each method). Mean values of friction coefficient (CoF) and wear rate (Kw) with confidence intervals ($P = 0.95$) are given in Table 5.

Table 5. Tribological characteristics of WC–Co–Cr coatings

Method	CoF (mean $\pm \sigma$, $P = 0.95$)	Kw, $\text{mm}^3/(\text{N}\cdot\text{m})$ ($P = 0.95$)	N samples
DS	0.545 ± 0.018	$(3.8 \pm 0.4) \times 10^{-6}$	3
HVOF	0.143 ± 0.012	$(1.2 \pm 0.2) \times 10^{-6}$	3
<i>Note – compiled by the authors</i>			

The DS coating (Fig. 9) is characterized by a pronounced run-in period with a sharp rise in CoF to ~ 0.48 – 0.50 and subsequent increase to ~ 0.60 ; mean CoF = 0.545 ± 0.018 ($P = 0.95$, $N = 3$). The HVOF coating demonstrates rapid CoF stabilization at the initial stage of testing; mean CoF = 0.143 ± 0.012 ($P = 0.95$, $N = 3$), which is 3.8 times lower. Wear rate Kw: DS - $(3.8 \pm 0.4) \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$, HVOF - $(1.2 \pm 0.2) \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$. The HVOF coating demonstrates approximately 3 times higher wear resistance than the DS coating.

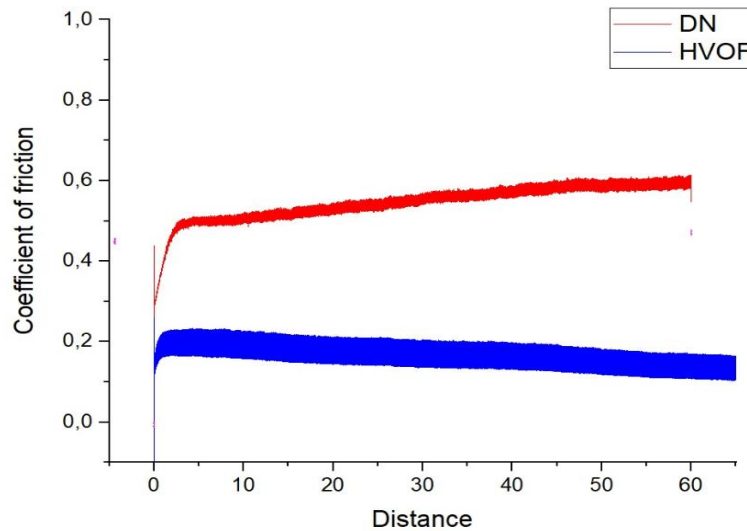


Figure 9. Friction coefficient of DS and HVOF WC–Co–Cr coatings as a function of sliding distance

Note – compiled by the authors

SEM analysis of coating surfaces after tribological tests (Fig. 10) confirmed the difference in wear mechanisms of the two coatings. The DS coating shows a wide wear track with mean width $\sim 778 \mu\text{m}$ ($L1 = 693.75 \mu\text{m}$; $L2 = 886.11 \mu\text{m}$; $L3 = 754.58 \mu\text{m}$), characterized by pronounced adhesive surface damage, areas of fracture, and material transfer from the counterbody. The HVOF coating demonstrates a significantly narrower and shallower wear track with mean width $\sim 565 \mu\text{m}$ ($L1 = 681.72 \mu\text{m}$; $L2 = 401.06 \mu\text{m}$; $L3 = 611.11 \mu\text{m}$); the surface outside the contact zone is virtually undamaged. The morphology of wear tracks is in qualitative agreement with the quantitative data on wear rate Kw and friction coefficient CoF given in Table 5, and confirms the higher tribological resistance of the HVOF coating under dry sliding conditions.

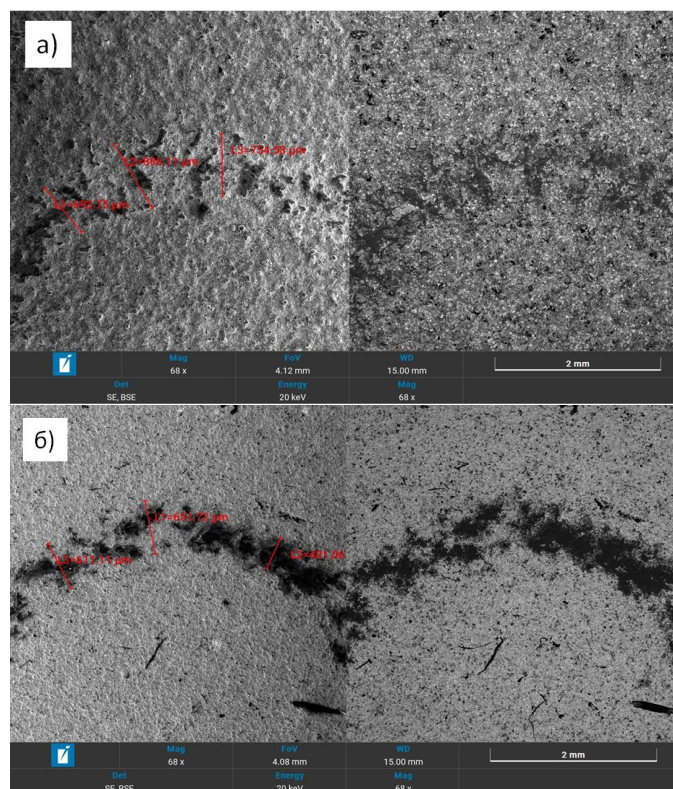


Figure 10. SEM images of wear tracks of WC–Co–Cr coatings:
(a) DS coating, (b) HVOF coating

Note – compiled by the authors

The obtained results are in good agreement with published data. Microhardness of HVOF WC–Co–Cr coatings, according to the literature, ranges from 1208 to 1415 HV (Picas *et al.*, 2009), consistent with 1317 ± 48 HV obtained in the present work. For HVOF WC–10Co–4Cr coating, microhardness was 1300 HV and dry sliding wear rate was $9.2 \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$ (Shu *et al.*, 2022) – a value higher than that obtained in the present work for HVOF ($(1.2 \pm 0.2) \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$), which may be attributable to differences in substrate material and test conditions. Comparative studies of WC–Co–Cr coatings deposited by HVOF and detonation spraying have shown that DS coatings demonstrate higher microhardness and erosion resistance compared to HVOF due to higher residual compressive stresses (Murthy, Rao and Venkataraman, 2001), consistent with the results of the present work (DS: 1449 ± 52 HV vs. HVOF: 1317 ± 48 HV). At the same time, a direct correlation between coating hardness and friction coefficient in WC–Co–Cr systems is not universal (Murthy, Rao and Venkataraman, 2001), which is confirmed in the present study: the harder DS coating is characterized by a significantly higher CoF (0.545) compared to HVOF (0.143).

The difference in tribological behavior of the coatings is due to their structural features. In the HVOF coating, pronounced inter-lamellar boundaries act as barriers to crack propagation under cyclic contact loading and ensure uniform contact interaction during sliding friction, resulting in a low and stable CoF. In the DS coating, the monolithic structure with minimal inter-lamellar boundaries causes increased adhesive interaction with the 100Cr6 steel counterbody, leading to an unstable friction regime and a higher CoF. Thus, the higher hardness of the DS coating does not compensate for its lower resistance to sliding wear, while the lamellar morphology of the HVOF coating is the determining factor of its tribological advantage (Méndez-Medrano *et al.*, 2018).

Thus, both methods provide high-quality WC–Co–Cr coatings on steel 20GL with different property balances. The DS coating outperforms HVOF in microhardness (1449 and 1317 HV respectively, $\Delta \approx 10\%$, $p < 0.001$), which determines its advantage under abrasive wear conditions. The HVOF coating substantially outperforms DS in tribological characteristics: friction coefficient 3.8 times lower (0.143 and 0.545 respectively), and wear rate approximately 3 times lower ($(1.2 \text{ and } 3.8) \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$ respectively), making it preferable for sliding friction conditions. The selection of spraying method should be based on the dominant loading mechanism of the component in specific service conditions.

CONCLUSIONS

This work presents a comprehensive comparative study of WC–Co–Cr cermet coatings deposited on structural steel 20GL by detonation (DS) and High Velocity Oxy-Fuel (HVOF) spraying. The analysis included assessment of starting powder morphology, microstructure and elemental composition of cross-sections (SEM and EDS), microhardness, and tribological characteristics under dry sliding conditions.

It is shown that the use of a homogeneous fully fused WC–Co–Cr powder of 20–40 μm fraction ensures the formation of dense, structurally uniform coatings by both methods, without visible cracks or delamination at the substrate interface. EDS mapping confirmed uniform distribution of W, C, Co, and Cr throughout the thickness of both coatings, consistent with the nominal composition of the starting powder.

Comparative analysis of mechanical and tribological properties revealed a fundamental difference in the balance of operational characteristics of the two coatings. The DS coating outperforms HVOF in microhardness: $1449 \pm 52 \text{ HV}$ vs. $1317 \pm 48 \text{ HV}$ ($\Delta \approx 10\%$, $p < 0.001$, Student's t-test). This is due to the pulsed nature of the detonation process, forming an ultra-dense structure with high dislocation density and compressive residual stresses. This advantage determines the suitability of DS coatings under abrasive wear conditions.

The HVOF coating substantially outperforms DS in tribological characteristics: friction coefficient 3.8 times lower (0.143 ± 0.012 vs. 0.545 ± 0.018), and wear rate approximately 3 times lower ($(1.2 \pm 0.2) \times 10^{-6}$ vs. $(3.8 \pm 0.4) \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$). SEM analysis of wear tracks confirmed these data: mean track width for the DS coating was $\sim 778 \mu\text{m}$ vs. $\sim 565 \mu\text{m}$ for HVOF. The determining factor of the tribological advantage of HVOF is the pronounced lamellar morphology of the coating: inter-lamellar boundaries act as barriers to crack propagation under cyclic contact loading and provide a low and stable friction coefficient. Thus, the higher hardness of the DS coating does not compensate for its lower resistance to sliding wear.

The obtained results indicate that the selection of spraying method cannot be based on a single criterion - hardness or tribological characteristics alone. The choice of technology must be determined by the dominant loading mechanism in specific service conditions: DS coating is preferable under abrasive wear, HVOF coating - under sliding friction and elevated tribological resistance requirements for machine components. The absence of XRD phase analysis represents a limitation of the current study; quantification of phase composition and decarburization effects is planned for future work.

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

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES: The authors declare that no generative AI or AI-assisted technologies were used in the preparation, writing, editing, data analysis, or interpretation of this manuscript.

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