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EFFECTS OF Cr_3C_2 -NICR POWDER PARTICLE SIZE AND SPRAYING DISTANCE ON THE STRUCTURE AND PROPERTIES OF HVOF-SPRAYED COATINGS

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ABSTRACT

This study investigates the effect of the particle size fraction of Cr_3C_2 -NiCr powder and of the spraying distance on the structure, porosity, and hardness of coatings deposited onto a 12Kh1MF steel substrate by high-velocity oxygen fuel (HVOF) spraying. Five samples were prepared: B1 (powder particle size 0–20 μm , spraying distance 300 mm), B2 (20–32 μm , 300 mm), B3 (32–40 μm , 300 mm), B4 (32–40 μm , 250 mm), and B5 (32–40 μm , 200 mm). The microstructure of the coatings was examined by scanning electron microscopy (SEM); porosity was determined from SEM images using ImageJ software; the elemental distribution was assessed by EDS mapping; and hardness was measured with a FISCHERSCOPE HM2000 instrumented indentation system in accordance with DIN EN ISO 14577-1. Increasing the powder particle size at a spraying distance of 300 mm was found to increase the coating thickness, but it may also increase porosity. The greatest coating thickness, $253.14 \pm 8.63 \mu\text{m}$, was obtained for sample B5, although its porosity reached 6.569%. The lowest porosity (2.909%) and the highest hardness were recorded for sample B4: $\text{HM} = 8063.2 \pm 619.5 \text{ N/mm}^2$, $\text{HV} = 1251.5 \pm 107.1$. The results show that, among the conditions studied, the optimal regime is the spraying of 32–40 μm powder at a distance of 250 mm, which ensures the formation of a denser and more uniform Cr_3C_2 -NiCr coating.

INTRODUCTION

Extending the service life of machine and equipment components that operate under intense wear, corrosion, erosion, and elevated temperatures is one of the pressing challenges of modern materials science and surface engineering. In many industrial sectors - mechanical engineering, power generation, oil and gas, transport, metallurgy, and aerospace - the working surfaces of components are simultaneously exposed to mechanical loads, abrasive particles, corrosive media, and cyclic temperature changes. Under such conditions the use of bulk expensive materials is not always economically justified; particular attention is therefore paid to the development of protective coatings that provide high hardness, wear resistance, corrosion resistance, and thermal stability of the surface while preserving the strength properties of the substrate (Chauhan et al., 2023; Eßler, 2025; Eßler et al., 2024).



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One of the most effective methods of producing wear-resistant coatings is high-velocity oxygen fuel (HVOF) spraying. The method is characterized by high particle velocity, a relatively moderate gas-flow temperature, and the ability to produce dense coatings with low porosity, good adhesion to the substrate, and a minimal content of oxide inclusions (He et al., 2022; Irfan et al., 2023). Unlike conventional thermal spraying methods, HVOF reduces overheating of the powder particles and minimizes decomposition of the carbide phase, which is particularly important for carbide-containing composite coatings. Owing to the combination of high particle kinetic energy and controlled thermal exposure, the method is widely used to deposit coatings based on WC-Co, WC-CoCr, Cr₃C₂-NiCr, and other cermet systems (Ksiazek & Łyp-Wrońska, 2024; Kurbanbekov et al., 2024; Lauzuardy et al., 2024).

Among carbide materials, Cr₃C₂-NiCr composite coatings are of particular interest. Their structure typically consists of hard Cr₃C₂ particles uniformly distributed in a NiCr metal matrix. The carbide phase provides high hardness and resistance to abrasive and erosive wear, whereas the nickel-chromium matrix enhances toughness, adhesion, corrosion resistance, and oxidation resistance. Owing to this combination of properties, Cr₃C₂-NiCr coatings are regarded as promising protective materials for components operating under friction in sulfide-containing solutions, high-temperature oxidation, and hot corrosion (Mahade et al., 2021). Despite the extensive research on Cr₃C₂-NiCr coatings, their properties depend to a large extent not only on the powder composition and the spraying parameters, but also on the characteristics of the feedstock powder: particle shape, particle size distribution, density, degree of agglomeration, carbide phase distribution, and the state of the metallic matrix. The particle size fraction is a particularly important factor, since particle size governs the heating, acceleration, melting, and deformation of the particles on impact with the substrate, and hence the formation of the lamellar structure of the coating (Oliveira et al., 2023; Ozkan, 2023; Saucedo et al., 2023).

In HVOF spraying, fine powder particles generally heat up faster and are accelerated more readily in the gas stream. This can promote a denser coating structure and reduce the number of large defects. However, excessively fine particles are prone to overheating, oxidation, partial dissolution of the carbide phase, and decarburization, which alters the phase composition and reduces the stability of Cr₃C₂. Coarser particles, in turn, have a greater mass and can retain high kinetic energy, but if they are insufficiently heated they do not deform completely on impact with the surface. This can lead to the formation of unmelted particles, increased porosity, structural inhomogeneity, and reduced adhesion strength of the coating (Seitov et al., 2025).

The particle size fraction is thus one of the key factors determining the microstructure and service properties of HVOF-sprayed Cr₃C₂-NiCr coatings. Changes in particle size affect the coating thickness, surface roughness, porosity, microhardness, carbide phase distribution, oxide content, residual stresses, and wear resistance. The optimal particle size fraction must therefore ensure sufficient heating and acceleration of the particles without excessive decomposition of the chromium carbide and without the formation of a large number of defects in the coating (Shi et al., 2022; Wang et al., 2021).

Accordingly, the aim of this study was to investigate the effect of the particle size fraction of Cr₃C₂-NiCr powder and of the spraying distance on the structure and hardness of coatings produced by the HVOF method. To this end, coatings deposited from powders of different particle size fractions were compared by scanning electron microscopy, energy-dispersive X-ray spectroscopy, porosity measurement, and instrumented indentation. This approach makes it possible to identify the powder particle size that ensures the formation of a dense and uniform Cr₃C₂-NiCr coating.

The scientific significance of this work lies in establishing the relationship between the particle size of the feedstock powder and the structural and mechanical properties of HVOF-sprayed Cr₃C₂-NiCr coatings. Its practical significance lies in the possibility of optimizing the

choice of powder material for coatings with enhanced durability, which can be used to protect components operating under abrasive wear, erosion, corrosion, and high-temperature exposure.

MATERIALS AND METHODS

Heat-resistant low-alloy 12Kh1MF steel, which is used for components operating at elevated temperatures and under mechanical loads, was selected as the substrate material. Its chemical composition is given in Table 1. The main alloying elements are chromium, molybdenum, and vanadium, which increase heat resistance, thermal stability, and oxidation resistance.

Table 1. Chemical composition of 12Kh1MF steel, wt. %

Element	C	Si	Mn	Cr	Mo	V	Ni	Cu	S	P	Fe
Content, wt. %	0.08-0.15	0.17-0.37	0.40-0.70	0.90-1.20	0.25-0.35	0.15-0.30	≤0.30	≤0.20	≤0.025	≤0.030	Base

Before spraying, the specimen surfaces were prepared mechanically. Grinding was carried out successively on SiC abrasive papers of progressively finer grades, from P120 to P2500. The specimens were then polished to the required surface finish and grit-blasted to produce the surface roughness needed for coating deposition.

A Cr_3C_2 -NiCr composite powder with different particle size fractions was used as the feedstock material. Cr_3C_2 -NiCr coatings form a carbide-metal system in which the chromium carbide Cr_3C_2 provides high hardness and wear resistance, while the NiCr metallic binder enhances toughness, adhesion, and oxidation resistance. To evaluate the effect of the powder particle size and the spraying distance, five samples, designated B1–B5, were prepared.

Samples B1–B3 were produced at the same spraying distance of 300 mm but from powders of different particle size fractions: 0–20, 20–32, and 32–40 μm . Samples B4 and B5 were sprayed with the 32–40 μm powder at shorter distances of 250 and 200 mm, respectively. This set of samples made it possible to evaluate the effect of both the powder particle size fraction and the spraying distance on the structure formation of HVOF-sprayed Cr_3C_2 -NiCr coatings.

Table 2. Conditions for producing the HVOF-sprayed Cr_3C_2 -NiCr coatings

Sample	Powder particle size, μm	Spraying distance, mm
B1	0–20	300
B2	20–32	300
B3	32–40	300
B4	32–40	250
B5	32–40	200

The coatings were deposited by high-velocity oxygen fuel (HVOF) spraying. In this method, powder particles are accelerated in a high-velocity gas stream and impact the substrate surface, where they deform, compact, and form a layered coating structure. Spraying was performed with a robotic manipulator, which ensured reproducibility of the process and identical parameters for all samples: powder feed rate, torch traverse speed, spraying time, and equipment operating mode. The same Cr_3C_2 -NiCr system was used for all samples; the only variables were the powder particle size and the spraying distance. During HVOF spraying it is essential to ensure sufficient heating and acceleration of the powder particles. Fine particles heat up faster and are accelerated more readily in the gas stream, which can promote the formation of a denser coating; however, excessive heating of fine particles may cause partial oxidation or decomposition of the carbide phase. Coarser particles, by contrast, retain higher kinetic energy

but, if insufficiently heated, deform less effectively on impact with the substrate. Investigating the effect of the particle size fraction is therefore an essential step in selecting the optimal conditions for coating formation.

After spraying, cross-sections of the coatings were prepared for examination. The samples were sectioned, ground successively, and polished to a smooth surface. The microstructure of the cross-sections was examined by scanning electron microscopy on a TESCAN VEGA microscope (Tescan, Brno, Czech Republic). The SEM images were used to evaluate the coating thickness, the structural density, the presence of pores, cracks, and unmelted particles, and the quality of coating adhesion to the substrate.

The porosity of the coatings was determined from SEM images of the cross-sections using ImageJ software. Several fields were analyzed for each coating. Image processing consisted of identifying the porous regions and calculating their area relative to the total area of the analyzed field; porosity was expressed as a percentage. This approach allowed a quantitative comparison of the density of coatings produced with different powder particle sizes and spraying distances. cross-section were analyzed using ImageJ software. Porosity was determined by image thresholding as the percentage ratio of the total pore area to the analyzed coating area. Five measurements were performed for each sample, and the results were expressed as the mean value $\pm$ standard deviation.

The hardness of the coatings was measured with a FISCHERSCOPE HM2000 instrumented indentation system (Helmut Fischer GmbH, Sindelfingen, Germany) in accordance with DIN EN ISO 14577-1. Measurements were made on the coating cross-sections. Several indentations were made at different locations for each sample, and the mean hardness was then calculated. The results were used to evaluate the effect of the powder particle size fraction and the spraying distance on the mechanical properties of the HVOF-sprayed Cr₃C₂-NiCr coatings.

RESULTS AND DISCUSSION

Figure 1 shows SEM images of cross-sections of HVOF-sprayed Cr₃C₂-NiCr coatings deposited on 12Kh1MF steel at different powder particle sizes and spraying distances. Analysis of the cross-sections makes it possible to assess the features of coating formation: thickness, density, the presence of pores, defects, and unmelted particles, and the quality of adhesion to the substrate.

The SEM images show that the powder particle size fraction and the spraying distance have a marked effect on the formation of the coating structure. All samples exhibit the layered structure typical of thermally sprayed coatings, which forms through the successive impact, deformation, and compaction of powder particles on the substrate surface.

Sample B1, produced from 0–20 μm powder at a distance of 300 mm, has the thinnest coating. Its cross-section reveals a thin layer with isolated inhomogeneous regions. This may be because finer particles heat up and accelerate more rapidly in the gas stream but, over a distance of 300 mm, some of them lose kinetic energy before reaching the substrate surface. As a result, the deposition efficiency decreases and a thinner coating forms.

In sample B2, obtained from 20–32 μm powder at the same distance of 300 mm, the coating is more pronounced and continuous than in B1. The larger particle size promotes more efficient transport of material to the substrate surface and the formation of a thicker layer, while the coating structure remains relatively dense, with no marked increase in porosity.

For sample B3, produced from 32–40 μm powder at a distance of 300 mm, the coating thickness increases, but the structure becomes more inhomogeneous, and porous and defective regions are visible. This may be because, at this spraying distance, coarser particles are not always fully heated and do not deform completely on impact with the substrate surface. The coating therefore becomes thicker but less dense.

A comparison of samples B3, B4, and B5 makes it possible to assess the effect of the spraying distance at the same powder particle size (32–40 μm). Sample B4, obtained at a distance of 250 mm, has a more uniform and denser structure, and its cross-section shows a fairly uniform coating with fewer pronounced defective regions. This indicates that a distance of 250 mm provides a more favorable combination of particle temperature and velocity, which promotes better deformation and compaction of the particles during coating formation.

Sample B5, produced at a distance of 200 mm, has a substantially greater coating thickness; its structure, however, contains porous and non-uniform regions. This shows that reducing the spraying distance to 200 mm leads to intense deposition of material but does not necessarily improve coating quality. At too short a distance, particles may strike the surface at high temperature and velocity, which can promote the formation of internal stresses and defects.

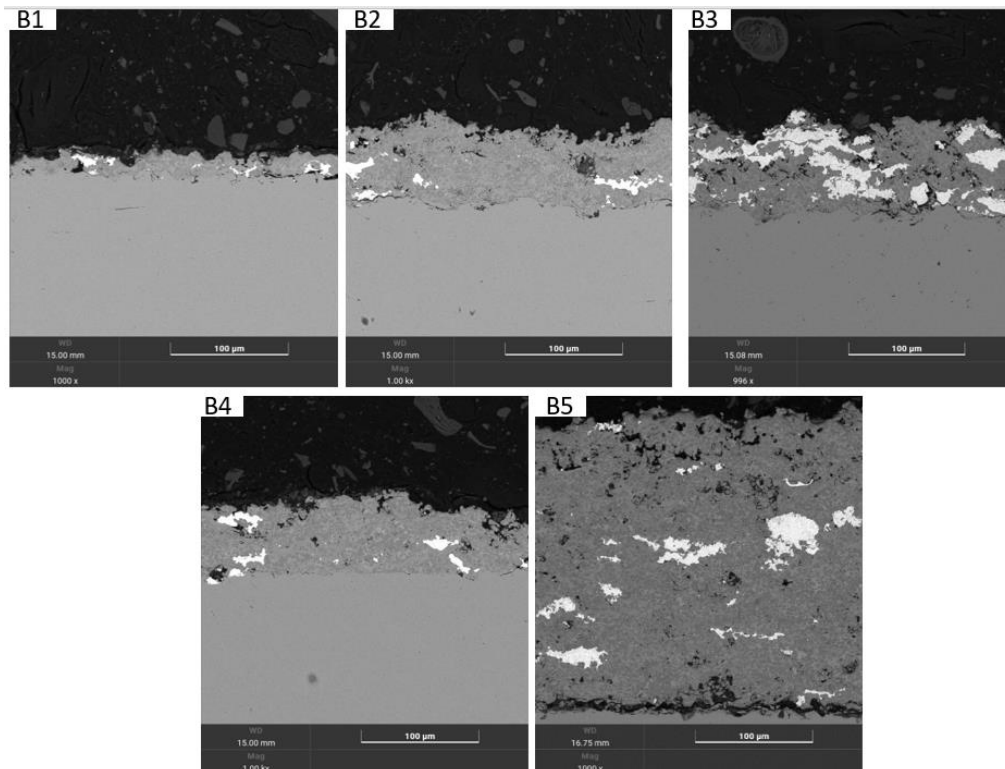


Figure 1. SEM images of cross-sections of the HVOF-sprayed Cr₃C₂-NiCr coatings

Figure 2 presents the results of the thickness and porosity measurements for the HVOF-sprayed Cr₃C₂-NiCr coatings. Thickness was measured on SEM images of cross-sections in three regions of each sample, and porosity was determined from binarized images in ImageJ.

The lowest mean coating thickness, $19.18 \pm 0.88 \mu\text{m}$, with a porosity of 3.047%, was recorded for sample B1. This may be attributed to the use of the fine 0–20 μm powder fraction at a spraying distance of 300 mm, over which the particles partly lose energy before reaching the substrate surface.

When the powder particle size was increased to 20–32 μm (sample B2), the thickness increased to $69.09 \pm 11.71 \mu\text{m}$ and the porosity was 3.206%. This indicates that this particle size fraction allows more efficient coating formation without a noticeable increase in porosity.

For sample B3, produced from 32–40 μm powder at a distance of 300 mm, the thickness was $78.83 \pm 11.19 \mu\text{m}$, but the porosity rose to 7.709%. This may be due to insufficient heating and deformation of the coarser particles, which leads to the formation of pores and defects.

A comparison of samples B3–B5 demonstrates the effect of the spraying distance at the same 32–40 μm powder fraction. When the distance was reduced to 250 mm, the thickness of sample B4 was $67.33 \pm 2.24 \mu\text{m}$ and the porosity fell to a minimum of 2.909%. This sample also showed the most uniform coating thickness.

A further reduction of the distance to 200 mm (sample B5) increased the thickness sharply, to $253.14 \pm 8.63 \mu\text{m}$, but the porosity also rose, to 6.569%. This indicates that a large coating thickness does not necessarily correspond to better coating quality.

The thickness and porosity data thus confirm the results of the SEM study. The most favorable conditions were those used for sample B4, produced from 32–40 μm powder at a spraying distance of 250 mm, which exhibits the lowest porosity, a uniform thickness, and a denser microstructure of the $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating on 12Kh1MF steel. Although samples B3–B5 were deposited using the same powder fraction (32–40 μm), their coating thicknesses differed because of the variation in spraying distance. The greater thickness of sample B5 can be attributed to the shorter spraying distance of 200 mm, which reduced the divergence of the particle jet and powder losses and increased the amount of material deposited per unit area. Consequently, a higher deposition efficiency and a thicker coating were obtained under this condition.

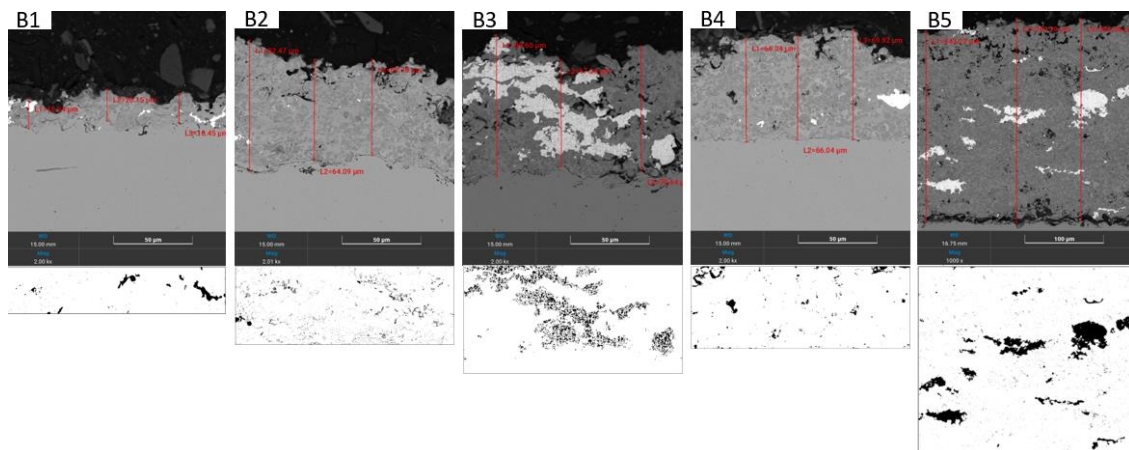


Figure 2. Thickness and porosity of the HVOF-sprayed $\text{Cr}_3\text{C}_2\text{-NiCr}$ coatings for samples B1–B5

Table 3. Thickness and porosity of the HVOF-sprayed $\text{Cr}_3\text{C}_2\text{-NiCr}$ coatings

Sample	Mean thickness, μm	Porosity, %
B1	19.18 ± 0.88	3.047
B2	69.09 ± 11.71	3.206
B3	78.83 ± 11.19	7.709
B4	67.33 ± 2.24	2.909
B5	253.14 ± 8.63	6.569

Figure 3 shows elemental distribution maps for the cross-sections of the $\text{Cr}_3\text{C}_2\text{-NiCr}$ coatings of samples B1–B5. The mapping data show that Fe is localized predominantly in the substrate region, which allows the boundary between the 12Kh1MF steel and the deposited coating to be identified clearly. In the coating zone the Fe concentration is much lower, which confirms the formation of a distinct sprayed layer.

Cr is distributed throughout the entire thickness of the coatings and corresponds to the Cr_3C_2 carbide phase. For samples B2, B4, and B5, the distribution of Ni associated with the NiCr

matrix is also clearly defined. The coexistence of Cr and Ni in the coating zone confirms the formation of a Cr_3C_2 -NiCr composite layer.

In samples B1 and B2 the coating is relatively thin, and Cr is distributed predominantly in the upper zone. Sample B3 shows a more inhomogeneous distribution of elements, which is consistent with the SEM images and its increased porosity. Local regions enriched in individual elements may indicate uneven melting and compaction of the powder particles at a spraying distance of 300 mm.

In sample B4, Cr and Ni are distributed more uniformly across the coating thickness, in agreement with its minimum porosity and the more homogeneous structure revealed by SEM. A spraying distance of 250 mm with a 32–40 μm powder fraction therefore promotes more stable coating formation and a uniform distribution of the main elements.

Sample B5 has the thickest coating; the elemental maps, however, reveal non-uniform regions, which is consistent with the increased porosity and the defective zones identified above. Despite the intense deposition of material at a distance of 200 mm, the coating structure remains less uniform than that of B4.

O, C, Si, and W are also detected in the distribution maps. The presence of oxygen may be associated with partial oxidation of the particles during HVOF spraying. Carbon belongs to the carbide component of the coating, although its quantitative determination by EDS is of limited accuracy. Localized Si- and W-rich regions may be related to features of the feedstock powder, to the surface preparation, or to process-related contamination.

EDS mapping thus confirms the formation of Cr_3C_2 -NiCr coatings on 12Kh1MF steel and reveals differences in the uniformity of elemental distribution depending on the spraying conditions. The most uniform distribution of the main elements and the densest structure are observed in sample B4, in agreement with the SEM results, the thickness measurements, and the porosity calculations.

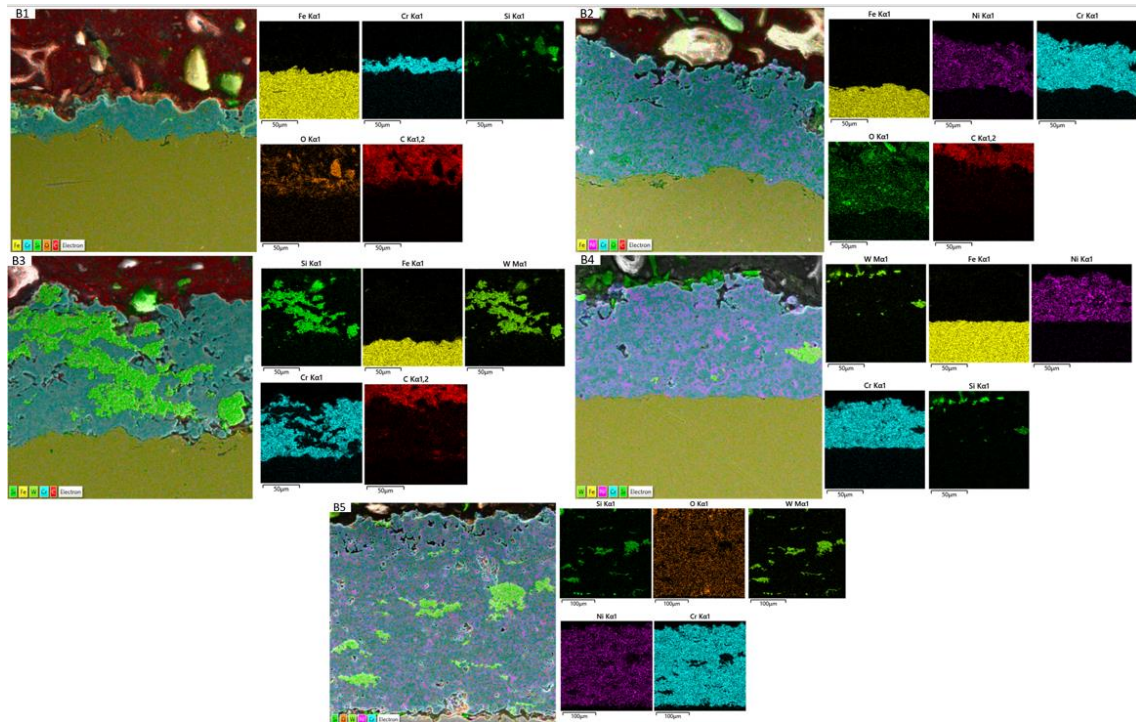


Figure 3. EDS maps of the elemental distribution in cross-sections of the HVOF-sprayed Cr_3C_2 -NiCr coatings for samples B1–B5

Instrumented indentation testing was carried out to evaluate the mechanical properties of the coatings. Figure 4 shows the load–penetration depth curves for samples B1–B5, and Table 4 lists the Martens hardness (HM), the indentation modulus $E_{it}/(1-\nu^2)$, and the Vickers hardness (HV).

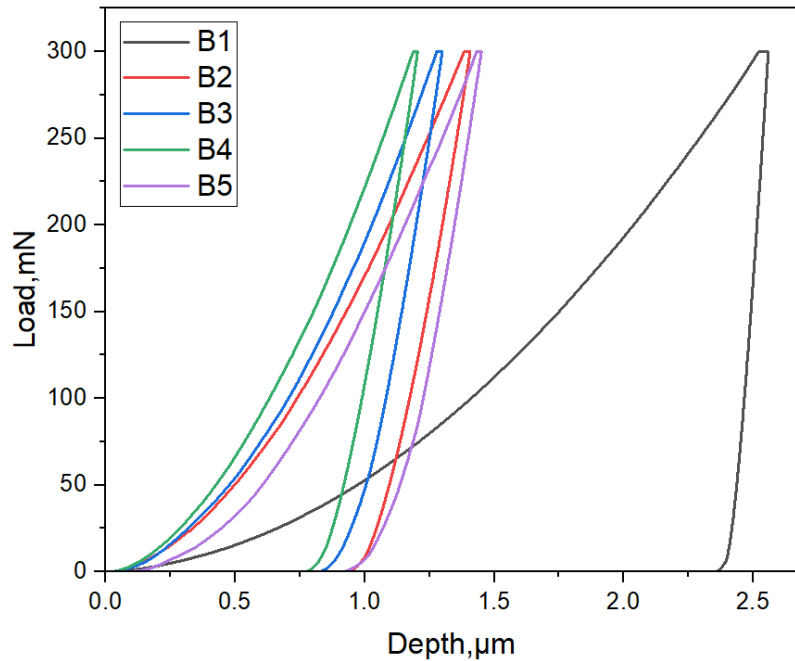


Figure 4. Load–penetration depth curves for the HVOF-sprayed Cr_3C_2 –NiCr coatings of samples B1–B5

Table 4. Instrumented indentation results for the HVOF-sprayed Cr_3C_2 –NiCr coatings

Sample	HM, N/mm ²	$E_{it}/(1-\nu^2)$, GPa	HV
B1	1759.0 ± 104.8	211.3 ± 1.3	198.7 ± 12.7
B2	6122.7 ± 1850.7	183.1 ± 45.0	928.0 ± 334.8
B3	7150.6 ± 1796.2	216.3 ± 38.8	1094.0 ± 330.5
B4	8063.2 ± 619.5	239.1 ± 21.1	1251.5 ± 107.1
B5	5447.7 ± 278.0	171.9 ± 6.7	809.6 ± 60.1

The lowest hardness values were recorded for sample B1: $\text{HM} = 1759.0 \pm 104.8 \text{ N/mm}^2$ and $\text{HV} = 198.7 \pm 12.7$. The load–penetration depth curve for this sample shows the greatest indenter penetration depth, which indicates low resistance to plastic deformation. This may be due to the small coating thickness and its less dense structure.

Samples B2 and B3 show a marked increase in hardness: $\text{HM} = 6122.7 \pm 1850.7$ and $7150.6 \pm 1796.2 \text{ N/mm}^2$, and $\text{HV} = 928.0 \pm 334.8$ and 1094.0 ± 330.5 , respectively. On the load–penetration depth curves this is reflected in a smaller indenter penetration depth. Increased porosity had, however, been observed in B3, which indicates a non-uniform coating structure.

The highest hardness was obtained for sample B4: $\text{HM} = 8063.2 \pm 619.5 \text{ N/mm}^2$, $E_{it}/(1-\nu^2) = 239.1 \pm 21.1 \text{ GPa}$, $\text{HV} = 1251.5 \pm 107.1$. This sample also shows one of the smallest indentation depths, which indicates high resistance to deformation. These results agree with the SEM analysis and the porosity data, according to which B4 has the densest and most uniform structure.

Sample B5 has a lower hardness than B4: $HM = 5447.7 \pm 278.0 \text{ N/mm}^2$, $E_{it}/(1-\nu^2) = 171.9 \pm 6.7 \text{ GPa}$, and $HV = 809.6 \pm 60.1$. Despite the considerable coating thickness, its mechanical properties are lower, which is attributed to the increased porosity and structural inhomogeneity. An increase in coating thickness therefore does not necessarily increase hardness.

Comparison of the results shows that the best combination of properties was obtained for sample B4, produced from 32–40 μm powder at a spraying distance of 250 mm; it combines high hardness, minimum porosity, and a more uniform microstructure. Samples B3 and B5 also have relatively high hardness values, but their quality is limited by increased porosity, whereas B1 shows the lowest values because of its thin coating and less dense structure.

CONCLUSIONS

HVOF-sprayed $\text{Cr}_3\text{C}_2\text{-NiCr}$ coatings deposited on 12Kh1MF steel from powders of different particle size fractions and at different spraying distances were investigated. The microstructure of the cross-sections, the coating thickness, the porosity, the elemental distribution, and the coating hardness were examined.

SEM analysis showed that the powder particle size fraction and the spraying distance significantly influence the formation of the coating structure. Sample B1, obtained from 0–20 μm powder at a spraying distance of 300 mm, had the smallest coating thickness, $19.18 \pm 0.88 \mu\text{m}$. When the powder particle size fraction was increased to 20–32 and 32–40 μm at the same spraying distance, the coating thickness increased to $69.09 \pm 11.71 \mu\text{m}$ for B2 and $78.83 \pm 11.19 \mu\text{m}$ for B3.

Increasing the powder particle size at a distance of 300 mm was found to increase the coating thickness; for sample B3, however, this was accompanied by an increase in porosity to 7.709%, the highest value among the samples studied. This indicates that the coating forms less uniformly when the 32–40 μm fraction is sprayed at a distance of 300 mm.

Comparison of samples B3, B4, and B5 revealed a pronounced effect of the spraying distance at the same 32–40 μm powder fraction. When the distance was reduced to 250 mm, sample B4 showed the most favorable characteristics: a mean thickness of $67.33 \pm 2.24 \mu\text{m}$ and a porosity reduced to 2.909%. This sample was also characterized by a more uniform microstructure and fewer defective regions.

Sample B5, obtained at a distance of 200 mm, had the greatest coating thickness, $253.14 \pm 8.63 \mu\text{m}$; the porosity of this coating, however, was 6.569%, which indicates structural inhomogeneity and the presence of defective regions. An increase in coating thickness therefore does not necessarily improve its quality.

EDS mapping confirmed the formation of a $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating on the 12Kh1MF steel surface. Fe was concentrated predominantly in the substrate region, whereas Cr and Ni were localized in the coating zone. The most uniform distribution of the main elements was observed in sample B4, in agreement with the SEM results and the porosity assessment.

Instrumented indentation showed that the highest hardness was obtained for sample B4: $HM = 8063.2 \pm 619.5 \text{ N/mm}^2$, $E_{it}/(1-\nu^2) = 239.1 \pm 21.1 \text{ GPa}$, $HV = 1251.5 \pm 107.1$. The lowest hardness was recorded for sample B1, which is attributed to its small thickness and less developed coating structure. Sample B5, despite having the greatest thickness, showed a lower hardness than B4 because of its increased porosity and structural inhomogeneity.

On the basis of the results obtained, it can be concluded that the optimal conditions among those investigated are those of sample B4, produced from $\text{Cr}_3\text{C}_2\text{-NiCr}$ powder with a particle size of 32–40 μm at a spraying distance of 250 mm. These conditions provide a combination of minimum porosity, high hardness, uniform thickness, and a denser coating microstructure.

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