International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Study on the Effect of WC-10Ni Content on the Surface Roughness, Porosity, and Microhardness of NiCrBSi/WC-10Ni Coatings

Nguyen Ngoc Quy[1*]
[1]Faculty of Mechanical Engineering Fundamentals, Tran Dai Nghia University, Ho Chi Minh, Viet Nam
[*]Corresponding author: ngocquymta@gmail.com

Abstract**—** *This study investigates the effect of WC-10Ni content on the surface roughness, porosity, and microhardness of NiCrBSi/WC-10Ni coatings fabricated by High Velocity Oxygen Fuel (HVOF) spraying. WC-10Ni powder was blended with NiCrBSi powder at weight ratios of 10%, 20%, and 30%, and subsequently sprayed onto C45 steel substrates. The results indicate that the surface roughness ranged from 5.192 to 6.087 µm, porosity varied from 1.684 to 3.544%, and microhardness ranged from 735.4 to 1090.4 HV0.3. Among the investigated compositions, the Ni20W coating (20 wt.% WC-10Ni) exhibited the most optimal performance, with the lowest surface roughness (Ra = 5.392 µm), the lowest porosity (2.573%), and the highest microhardness (1073.4 HV0.3). These findings confirm that a WC-10Ni content of 20 wt.% represents the optimal blending ratio for NiCrBSi/WC-10Ni coatings deposited by HVOF spraying.*

Keywords**—** *WC-10Ni, NiCrBSi coating, HVOF, surface roughness, porosity, microhardness.*

I. INTRODUCTION

Thermal spray coatings are among the most advanced technological solutions widely applied to enhance wear resistance, corrosion resistance, and extend the service life of mechanical components operating under severe conditions. Among various thermal spraying techniques, High Velocity Oxygen Fuel (HVOF) spraying is particularly prominent due to its ability to produce coatings with high density, low porosity, and strong adhesion to substrate materials.

NiCrBSi alloy is commonly used for the fabrication of wear-resistant coatings because of its relatively high hardness, excellent corrosion resistance, and superior wear resistance at elevated temperatures [1]. However, to further improve the mechanical properties of NiCrBSi coatings, numerous studies have incorporated hard reinforcing particles such as WC, Cr_3C_2, and TiC into the NiCrBSi matrix [2]. Tungsten carbide (WC) is one of the most widely utilized reinforcing materials due to its exceptionally high hardness. Nevertheless, WC may undergo decarburization into less hard phases such as W_2C and W during the high-temperature spraying process, thereby reducing its reinforcement effectiveness. Therefore, WC-10Ni powder (90% WC in a 10% Ni matrix) is employed to minimize decarburization and improve coating durability [3].

Surface roughness, porosity, and microhardness are three critical mechanical parameters that reflect coating quality. Lower surface roughness generally indicates a more uniform coating structure with fewer defects, while higher hardness enhances the coating's ability to withstand contact loads and resist wear. Although several studies have investigated NiCrBSi/WC-Co coatings [4], detailed research focusing on NiCrBSi/WC-10Ni coatings, particularly regarding the relationship between blending ratio, surface roughness, and hardness, remains limited. This paper presents the results of an investigation into the effects of WC-10Ni blending ratios (10%, 20%, and 30% by weight) on the surface roughness, porosity, and microhardness of NiCrBSi/WC-10Ni coatings deposited by HVOF spraying, thereby identifying the optimal composition for achieving superior coating quality.

II. EXPERIMENTAL PROCEDURE

A. Preparation of Spray Materials

The spray materials consisted of blended NiCrBSi and WC-10Ni powders with a particle size range of -45/+15 µm. According to the manufacturer, BODA (China), the primary chemical composition of the powders was as follows: NiCrBSi contained 83.43% Ni, 10.52% Cr, 2.10% B, and 3.95% Si, while WC-10Ni consisted of 90% WC and 10% Ni. Particle morphology analysis using a Camsizer X2 revealed that 90% of the WC-10Ni particles had a size below 44.3 µm, while particles larger than 45 µm accounted for 8.25%.

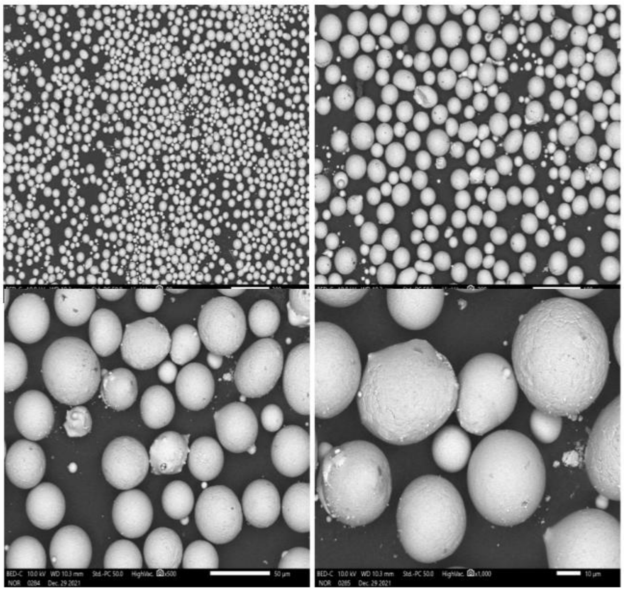


Figure 1. SEM image of NiCrBSi spray powder.

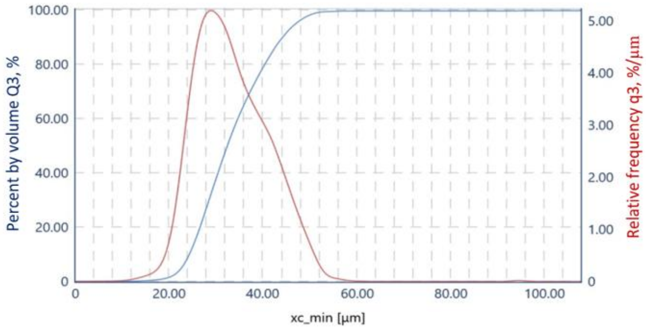


Figure 2. Particle size distribution of WC-10Ni powder by volume.

Table 1 lists the five coating samples investigated in this experimental study. The raw powders were mechanically blended using a SH Scientific Ball Mill at a rotational speed of 312 rpm for 30 minutes to ensure mixture homogeneity.

TABLE 1. Abbreviations of the coating samples.

No.	Coating composition	Abbreviation
1	NiCrBSi	Ni
2	NiCrBSi + 10%WC-10Ni	Ni10W
3	NiCrBSi + 20%WC-10Ni	Ni20W
4	NiCrBSi + 30%WC-10Ni	Ni30W
5	WC-10Ni	W

B. *Coating fabrication*

The coating experiments were conducted on C45 steel substrates with dimensions of Ø60 × 20 mm. The substrate surfaces were cleaned with acetone, followed by surface activation using aluminum oxide grit blasting to achieve a surface roughness of Ra ≥ 6.2 µm, thereby enhancing coating adhesion to the substrate.

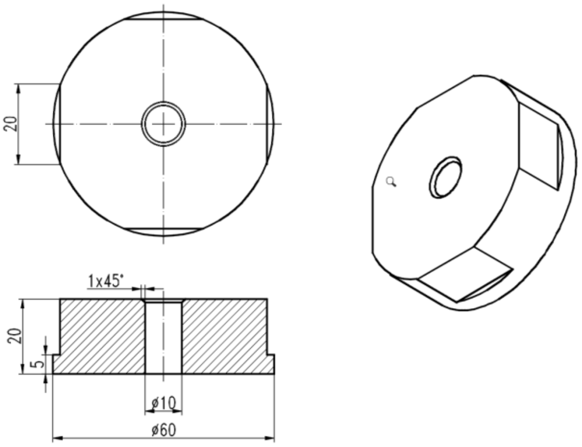


Figure 3. Design drawing of the experimental specimen.

TABLE 2. Processing parameters for coating fabrication.

Parameters	Value
Oxygen flow rate (L/min)	130
LPG flow rate (L/min)	40
Spray distance (mm)	280
Powder feed rate (g/min)	35-45
Substrate surface speed (mm/s)	630
Relative movement speed between spray gun and substrate (mm/s)	3

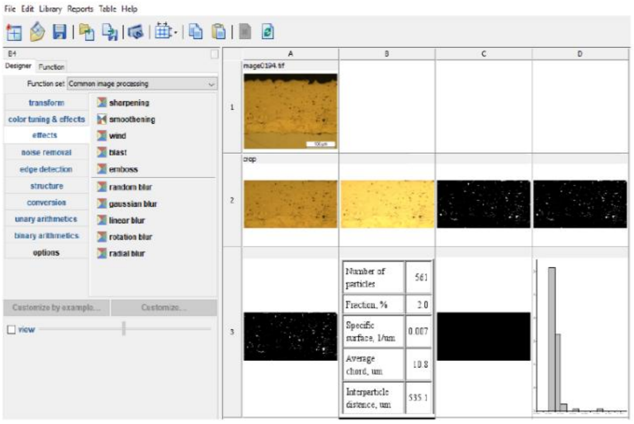
A water-cooled hybrid HVOF spray gun was employed with consistent processing parameters for all coating samples, as presented in Table 2. The coating thickness was approximately 300 µm. The substrate temperature was controlled below 200°C throughout the spraying process.

C. *Evaluation methods*

The surface roughness of the coatings was measured in accordance with ISO 4288:1996 using a Mitutoyo SJ-410 surface roughness tester, with a sampling length of 10 mm and a cut-off length of 2.5 mm. Each sample was measured five times at different locations, and the reported result represents the average value.

Figure 4. Measurement of coating surface roughness using the Mitutoyo SJ-410.

The coating porosity was determined in accordance with ASTM E2109 by analyzing cross-sectional images captured using a Leica DMi8M optical microscope and processed with SIAMS 700 software. This parameter serves as a fundamental basis for explaining variations in surface roughness and microhardness.



Number of particles	561
Fraction, %	2.0
Specific surface, 1/um	0.007
Average chord, um	10.8
Interparticle distance, um	535.1

Figure 5. Porosity calculation using SIAMS 700 software.

Vickers microhardness was measured using an HV-1000ZDT microhardness tester in accordance with ISO 6507:2005. A test load of 300 gf was applied with a dwell time of 10 seconds. Each sample was measured five times along the coating thickness direction, and the reported value represents the average result.

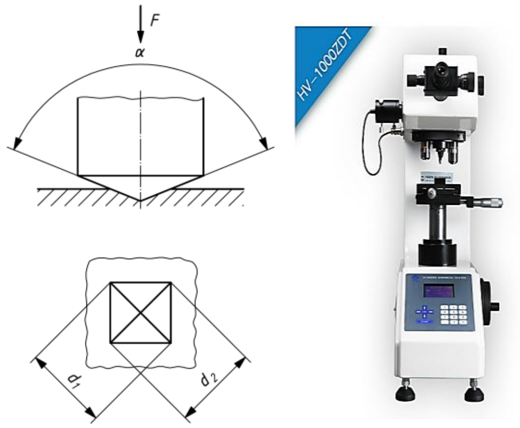


Figure 6. Vickers indentation marks and the HV-1000ZDT microhardness tester.

III. RESULT AND DISCUSSION

A. *Effect of WC-10Ni Content on Surface Roughness*

Surface roughness is a key reference parameter reflecting the surface quality of sprayed coatings, primarily influenced by powder particle size, spraying equipment, and processing parameters. The average surface roughness results of the five coating samples are presented in Figure 7.

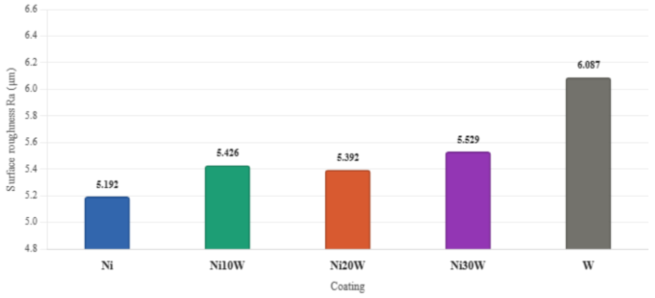


Figure 7. Average surface roughness values of the sprayed coating samples.

Analysis of the results presented in Figure 7 reveals several distinct trends:

First, the pure NiCrBSi coating (Ni) exhibited the lowest surface roughness, with Ra = 5.192 µm. This is attributed to the lower melting temperature of NiCrBSi particles, which allows most particles to melt completely and deform effectively upon impact with the substrate surface, thereby producing a smoother and more uniform coating surface.

Second, as the WC-10Ni content increased, the surface roughness generally showed an increasing trend. Specifically, the Ni10W coating achieved Ra = 5.426 µm, Ni30W reached Ra = 5.529 µm, and the pure WC-10Ni coating exhibited the highest roughness at Ra = 6.087 µm. This behavior is primarily due to the significantly higher melting temperature of WC-10Ni compared to NiCrBSi, resulting in partial melting of some WC-10Ni particles during the spraying process. These incompletely melted particles create irregular protrusions and depressions upon impact, thereby increasing surface roughness.

Third, it is noteworthy that the Ni20W coating demonstrated a surface roughness of Ra = 5.392 µm, which was lower than both Ni10W (5.426 µm) and Ni30W (5.529 µm). This indicates that at a WC-10Ni content of 20 wt.%, the distribution of the two material phases reached the most uniform state, minimizing localized accumulation of unmelted WC particles. This result strongly correlates with the lowest porosity observed in the Ni20W coating among the blended coatings, reflecting a denser and more homogeneous microstructure. The lower surface roughness also suggests that the Ni20W coating is likely to exhibit superior erosion resistance and tribological performance.

B. *Effect of WC-10Ni Content on Coating Porosity*

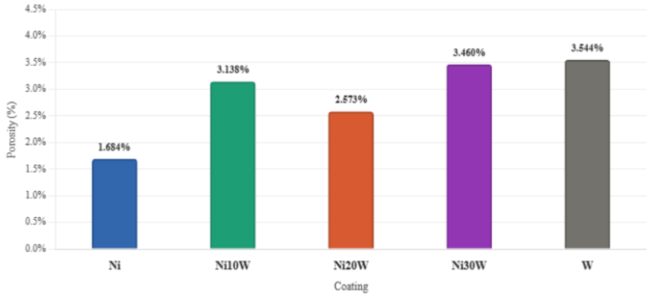


Figure 8. Average porosity evaluation results of the coating samples.

Analysis of the results presented in Figure 8 provides several important observations regarding the influence of WC-10Ni content on coating porosity:

First, the pure NiCrBSi coating (Ni) exhibited the lowest porosity at 1.684%. This is attributed to the relatively low melting temperature of NiCrBSi particles, which allows most particles to melt completely during spraying, deform effectively, and fill voids upon impact with the substrate surface.

Second, as the WC-10Ni content increased, coating porosity generally increased. The pure WC-10Ni coating (W) showed the highest porosity, reaching 3.544%. This is mainly due to the significantly higher melting temperature of WC-10Ni (>2700°C) compared to NiCrBSi (~1000°C), resulting in a considerable proportion of WC-10Ni particles remaining partially unmelted during spraying. When these semi-molten particles impact the substrate, they do not deform or flatten effectively, leading to the formation of voids and interlamellar gaps.

Third, it is noteworthy that the Ni20W coating exhibited a porosity of 2.573%, which was lower than both Ni10W (3.138%) and Ni30W (3.460%). This can be explained by the fact that at a 20 wt.% WC-10Ni content, NiCrBSi still constitutes the dominant phase (80%), providing a sufficiently continuous molten matrix capable of surrounding and filling the voids around partially unmelted WC-10Ni particles. In contrast, at 30 wt.% WC-10Ni (Ni30W), the excessive concentration of WC-10Ni particles promotes localized pore formation at phase boundaries, while the reduced amount of molten NiCrBSi becomes insufficient to compensate for these defects.

The porosity results strongly correlate with the measured surface roughness values: the Ni20W coating not only exhibited the lowest porosity among the blended coatings but also demonstrated the lowest surface roughness, indicating a dense and homogeneous microstructure consistently reflected by both parameters.

C. Effect of WC-10Ni Content on Microhardness

Microhardness is the most critical parameter reflecting the load-bearing capacity and wear resistance of coatings. The Vickers microhardness (HV0.3) results of the coating samples are presented in Figure 9.

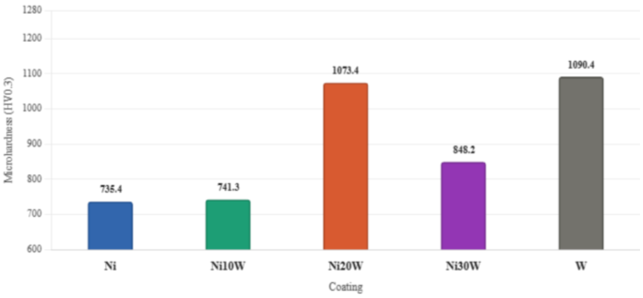


Figure 9. Vickers microhardness values (HV0.3) of the coating samples.

The results shown in Figure 9 clearly demonstrate the influence of WC-10Ni content on coating hardness:

The pure NiCrBSi coating (Ni) exhibited the lowest hardness, at 735.4 HV0.3. With the addition of WC-10Ni into the NiCrBSi matrix, the coating hardness increased significantly. Due to the exceptionally high hardness of WC (approximately 2400 HV), WC particles act as hard reinforcing phases within the NiCrBSi matrix, hindering plastic deformation and substantially improving the overall hardness of the coating.

Among the blended coatings, the Ni20W coating achieved the highest hardness, reaching 1073.4 HV0.3, which is approximately 46% higher than that of the pure NiCrBSi coating. This improvement can be attributed to two primary mechanisms: (1) a more uniform distribution of hard WC particles within the NiCrBSi matrix, and (2) the lowest porosity among the blended coatings (2.573%), resulting in a denser microstructure where Vickers indentations are less affected by surrounding pores.

When the WC-10Ni content increased to 30 wt.%, the hardness decreased to 848.2 HV0.3, which was notably lower than that of Ni20W. This reduction is mainly due to the excessive WC particle concentration, which promotes non-uniform clustering of WC particles, increases localized porosity at phase boundaries, and creates mechanical weak points. Furthermore, increased decarburization (formation of W_2C) at higher WC content may reduce the reinforcement effectiveness.

The pure WC-10Ni coating exhibited the highest hardness overall, reaching 1090.4 HV0.3. However, considering the balance between hardness, material cost, and overall mechanical performance, the Ni20W coating demonstrated the most optimal performance among all investigated samples.

D. Correlation Between Surface Roughness, Porosity, and Microhardness

A comprehensive analysis of surface roughness, porosity, and microhardness reveals a consistent relationship among these three parameters: the Ni20W coating simultaneously achieved the lowest surface roughness, the lowest porosity, and the highest microhardness among the blended coatings. This indicates that at a WC-10Ni content of 20 wt.%, the balance between the two material phases, NiCrBSi and WC-10Ni, reached an optimal state. The lower-melting NiCrBSi matrix effectively surrounded and filled the voids between WC-10Ni particles, resulting in a denser and more homogeneous microstructure.

When the WC-10Ni content exceeded 20 wt.%, the increased proportion of high-melting-point WC particles led to a greater number of incompletely melted particles, creating weakly bonded phase boundaries, increasing porosity, elevating surface roughness, and ultimately reducing hardness compared to the Ni20W coating. This explains why the Ni30W coating exhibited lower hardness and higher roughness than Ni20W despite containing a higher WC fraction.

IV. CONCLUSION

This study investigated the effect of WC-10Ni content (10%, 20%, and 30% by weight) on the surface roughness, porosity, and microhardness of NiCrBSi/WC-10Ni coatings fabricated by HVOF spraying. The main conclusions are summarized as follows:

(1) The surface roughness of the coatings ranged from 5.192 to 6.087 µm and generally increased with increasing WC-10Ni content. The Ni20W coating exhibited the lowest surface roughness among the blended coatings (Ra = 5.392 µm), lower than both Ni10W and Ni30W, indicating a more uniform and stable surface structure at this composition.

(2) The coating porosity ranged from 1.684% to 3.544% and also showed an increasing trend with higher WC-10Ni content. The Ni20W coating achieved the lowest porosity among the blended coatings (2.573%), which was lower than that of Ni10W (3.138%) and Ni30W (3.460%), due to the sufficient amount of molten NiCrBSi matrix available to fill voids surrounding WC-10Ni particles.

(3) Microhardness increased significantly with the incorporation of WC-10Ni into the NiCrBSi matrix. The Ni20W coating exhibited the highest microhardness among the blended coatings, reaching 1073.4 HV0.3, which represents a 46% increase compared to the pure NiCrBSi coating (735.4 HV0.3). This improvement is attributed to the uniform distribution of WC reinforcing particles and the lowest porosity.

(4) When the WC-10Ni content increased to 30 wt.%, both surface roughness and porosity increased, while hardness decreased compared to Ni20W. This behavior resulted from incomplete melting of WC particles and the formation of non-uniform particle clusters at phase boundaries.

(5) A blending ratio of 20 wt.% WC-10Ni was identified as the optimal composition, simultaneously providing the lowest surface roughness, lowest porosity, and highest hardness among the blended coatings. This composition serves as a practical

basis for selecting NiCrBSi/WC-10Ni coating materials for industrial applications requiring high wear-resistant surfaces.

REFERENCES

[1] Y. H. Shieh et al., "Alloying and post-heat-treatment of thermal-sprayed coatings of self-fluxing alloys," *Surface and Coatings Technology*, vol. 58, no. 1, pp. 73–77, 1993.

[2] A. García et al., "Study of the sliding wear and friction behavior of WC + NiCrBSi laser cladding coatings," *Tribology Letters*, vol. 63, no. 3, 2016.

[3] N. A. Ahmad et al., "Characterization of WC-10Ni HVOF coating for carbon steel blade," *IOP Conference Series: Materials Science and Engineering*, vol. 165, p. 012022, 2017.

[4] H. Guo et al., "Effect of WC–Co content on the microstructure and properties of NiCrBSi composite coatings fabricated by supersonic plasma spraying," *Journal of Alloys and Compounds*, vol. 789, pp. 966–975, 2019.

[5] R. Rachidi et al., "Microstructure and mechanical characterization of NiCrBSi alloy and NiCrBSi-WC composite coatings produced by flame spraying," *Materials Science and Engineering B*, vol. 241, pp. 13–21, 2019.

[6] C. R. Ciubotariu et al., "Investigations of cavitation erosion and corrosion behavior of flame-sprayed NiCrBSi/WC-12Co composite coatings," *Materials*, vol. 15, no. 8, 2022.

[7] N. T. Binh, L. V. Canh, and P. H. Dong, "Oxygen-LPG torch for thermal spraying," in *Proceedings of the 6th International Conference on Green Technology and Sustainable Development*, Nha Trang, Vietnam, 2022, pp. 152–157.