International Journal of Energy and Applied Sciences

Effect of Hvof Process Parameters on The Structure And Mechanical Performance of Zrcn Coatings

Sherzod Kurbanbekov[1], **Alfiya Kamalova**[1]*, **Shukur Abduzhapparov**[1] **and Diyar Patchakhanov**[1]

[1]Kh. A. Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan; alfia.kamalova.2024@ayu.edu.kz, sherzod.kurbanbekov@ayu.edu.kz, shukurabdujapparov24@gmail.com, itsxxdi@gmail.com;
*Correspondence: alfia.kamalova.2024@ayu.edu.kz.

Received: 12 April 2026
Revised: 22 April 2026
Accepted: 4 May 2026
Published: 25 May 2026

https://doi.org/10.47526/2026-1/2505-3123.01

Abstract

The paper investigates the structural and mechanical properties of zirconium carbonitride (ZrCN) coatings deposited by high-velocity oxygen flame spraying (HVOF) on a U8G steel substrate. The effect of spraying process parameters on the adhesion strength and microhardness of the coatings is considered. It is established that changing the HVOF modes significantly affects the formation of the microstructure, density and quality of the coating–substrate interphase boundary. All the obtained coatings are shown to have high microhardness, exceeding that of the original material by more than 4–5 times. The maximum values of both adhesion strength and microhardness are achieved at optimal spraying parameters (mode c), which is associated with improved particle flattening, reduced porosity and the formation of a denser coating structure. The obtained results confirm the potential of using ZrCN coatings obtained by the HVOF method to increase the wear resistance and durability of parts operating under conditions of intense mechanical and thermal loads.

Keywords: ZrCN; HVOF; protective coatings; adhesion; microhardness; wear resistance; microstructure.

1. Introduction

Today, U8G carbon tool steel is widely used in mechanical engineering and toolmaking for the manufacture of cutting tools, spring elements, and components that operate without significant heating of the working edge. Due to its combination of sufficient hardness, processability, and relative affordability compared to alloy steels, this material remains in demand in mass production and for creating components with elastic and wear-resistant properties. However, U8G steel has several disadvantages, such as limited wear resistance, a tendency to intense surface wear, and instability of friction properties, limiting its use in loaded tribo-joints. This has led to interest in its research as a base material for subsequent hardening.

The growing demand for new materials with improved mechanical and tribological properties has stimulated research in surface engineering. Various coatings have been developed, such as diamond-like carbon, nitrides, carbides, and carbonitrides of transition metals [1-20]. Coatings based on zirconium carbonitride (ZrCN) are of particular interest among wear-resistant protective coatings due to their combination of high hardness, chemical and thermal stability, and improved tribological properties. The introduction of carbon into the zirconium nitride structure leads to the formation of a modified microstructure that provides increased wear resistance, a reduced friction coefficient, and resistance to surface failure under mechanical loads. These properties make ZrCN coatings promising for use in friction units and machine parts operating under conditions of intense wear and elevated temperatures [21]. Additional data confirm that multilayer and composite coatings based on ZrCN systems exhibit high mechanical properties and a stable microstructure, contributing to improved tool performance. Comparative tests of such coatings have noted improved performance and wear resistance, which emphasizes the potential of zirconium group materials as an alternative to traditional nitride coatings [22].

ZrCN-based coatings, including physical and chemical vapor deposition, as well as thermal spray methods. One of the most effective and promising methods is HVOF. Due to recent advances in the production of high-quality nanoscale powders, including atomization, colloidal deposition, mechanical milling, as well as nucleation and growth in the vapor phase [23-26], the focus of nanostructured materials research is shifting from synthesis to processing, for example, to the fabrication of nanostructured coatings using HVOF [27-28]. Nanostructured coatings are widely tested in many industries as heat-protective and wear-resistant surface layers to extend the service life of products, improve productivity, and reduce production and repair costs. This method is based on the combustion of a fuel mixture with oxygen, producing a high-speed (supersonic) jet of combustion products. Powder particles are introduced into this jet, heated, accelerated, and deposited on the substrate surface, forming a dense and durable coating.

The HVOF method produces coatings with high adhesion, low porosity, and a uniform microstructure, significantly improving their performance characteristics. This makes this method particularly in demand in industries such as mechanical engineering, energy, and aviation.

Studying the structure and properties of ZrCN coatings is an important step in understanding their behavior under various operating conditions and optimizing their application process parameters. Particular attention is paid to analyzing the microstructure, phase composition, and mechanical properties of the coatings, as these parameters determine their wear resistance, adhesion to the substrate, and durability.

Thus, this study aims to investigate and optimize the process of applying ZrCN-based coatings by the HVOF method, as well as to analyze their structural and performance characteristics.

The aim of this work is to study the adhesion and microhardness of the ZrCN coating applied by the HVOF method onto a U8G steel substrate.

2. Materials and Methods

Among the various thermal spraying methods, HVOF occupies a special place as one of the most rapidly developing processes, providing coatings with high density and porosity of less than 1%. Coatings formed by the HVOF method are characterized by increased adhesion, hardness, and improved wear, erosion, and corrosion resistance, which contributes to a significant increase in the service life of the equipment. The high kinetic energy of the particles during spraying ensures the formation of a dense structure, and control of the cooling rate allows for the production of coatings up to 1.5 mm thick with reduced residual stress levels [29].

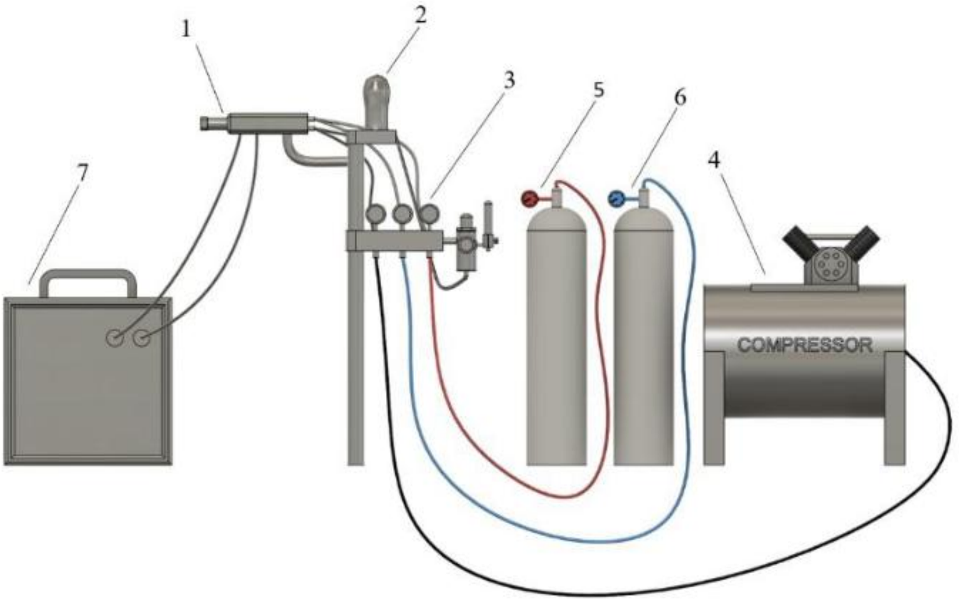

Figure 1. External appearance and design diagram of the HVOF system: 1 - burner; 2 - powder feeder; 3 - gas control panel; 4 - compressor; 5 - gas cylinder; 6 - gas cylinder (O); and 7 - chiller [30].

Upon exiting the torch, the powder particles enter the flame zone, where they are heated to a state that ensures their plastic deformation. The molten particles are then directed onto the pre-treated substrate surface, forming a uniform protective coating. ZrCN powder, with particle sizes in the 20–100 μm range, has an irregular polyhedral fragmented morphology, which is known to have lower flowability than spherical particles [30]. The main spraying parameters are presented in Table 1. U8G grade steel, a high-carbon alloy steel, was used as the substrate. Keeping other process parameters constant, varying the oxygen pressure allows for changes in the fuel-oxidizer ratio, which determines the thermodynamic combustion conditions in the HVOF chamber. This, in turn, affects the jet temperature, particle velocity, and the efficiency of powder deposition onto the substrate.

Table 1. Parameters used for applying the ZrCN coating to the U8G

No.	Distance, cm (plasma torch-sample)	Air, bar (Aır)	Oxygen, bar (Oxygen)	Propane, bar (Fuel)	Powder
Sample a	35-40	2.6	3.3	3	ZrCN
Sample b			3.5		
Sample c			3.7		

The microhardness of the sample and the resulting coatings was measured using a Vickers microhardness tester HLV-1DT. A diamond tetrahedral pyramid with 136° angles was used as an indenter. During the measurement, a load of HV0.5 was applied to the sample surface, and the indenter was held for 10 seconds. Then, the diagonal dimensions of the input traces (d1 and d2) were accurately determined [30-31]. To study the adhesive properties of the coatings, tests were conducted using an Elcometer 510 hydraulic adhesion meter (Elcometer Instruments, Manchester, UK).

3. Results and Discussion

The conducted research yielded experimental data characterizing the mechanical properties of zirconium carbonitride (ZrCN) coatings produced by the HVOF method under various process conditions. A comparative analysis of the coatings' adhesion strength and microhardness was conducted, and the influence of spraying parameters on their structure and performance characteristics was identified. To determine the adhesive strength of the coatings in this work, an Elcometer 510 adhesion meter was used, the operation of which is based on the pull-off test method.

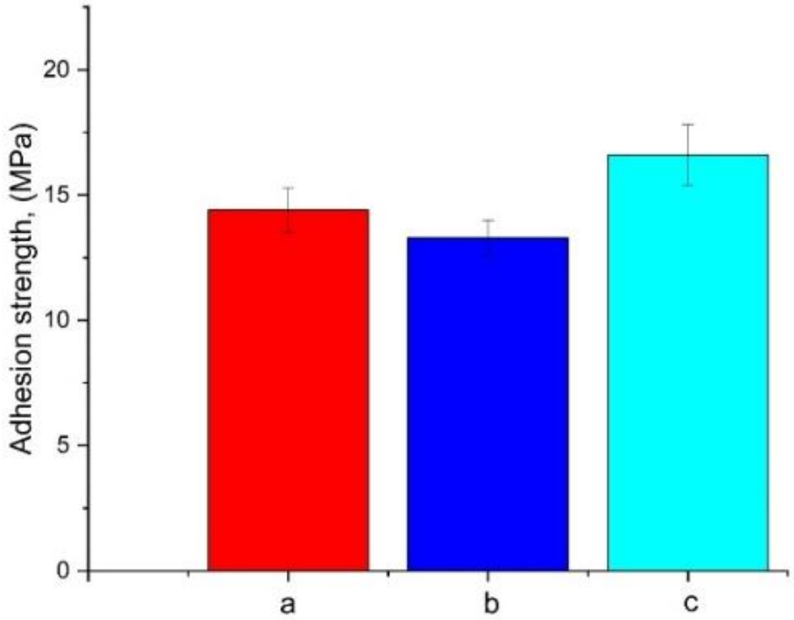

Figure 2. Dependence of the adhesion strength of ZrCN coatings on the HVOF spraying parameters.

Figure 2 shows the adhesion strength values for three coatings (a, b, c) produced using the same HVOF method from identical powder material but with different spraying parameters. The ordinate axis shows adhesion strength (MPa). While all three coatings exhibit similar values, there are significant differences between them, indicating a significant influence of spraying conditions on the formation of the coating-substrate interface.

Since the chemical composition of the powder and the application method are the same in all cases, differences in adhesion strength should be attributed to the technological parameters of the HVOF process, namely, the oxygen pressure parameter. From the diagram, it can be estimated that the adhesion strength of coating a is 14.4 MPa, coating b is 13.3 MPa, and coating c is approximately 16.6 MPa. Thus, the maximum adhesion value is characteristic of coating c, while the minimum is characteristic of coating b. The difference between the extreme values is approximately 3.3 MPa, which is equivalent to an increase in adhesion strength of approximately 25% when switching from mode b to mode c. Compared to coating a, coating c has an increase in adhesion of approximately 15%, while coating b is inferior to coating a by approximately 7-8%.

An optimal spraying regime usually results in reduced porosity in the contact zone and a reduction in the number of weakly bonded areas that can serve as stress concentrators during a pull-off test.

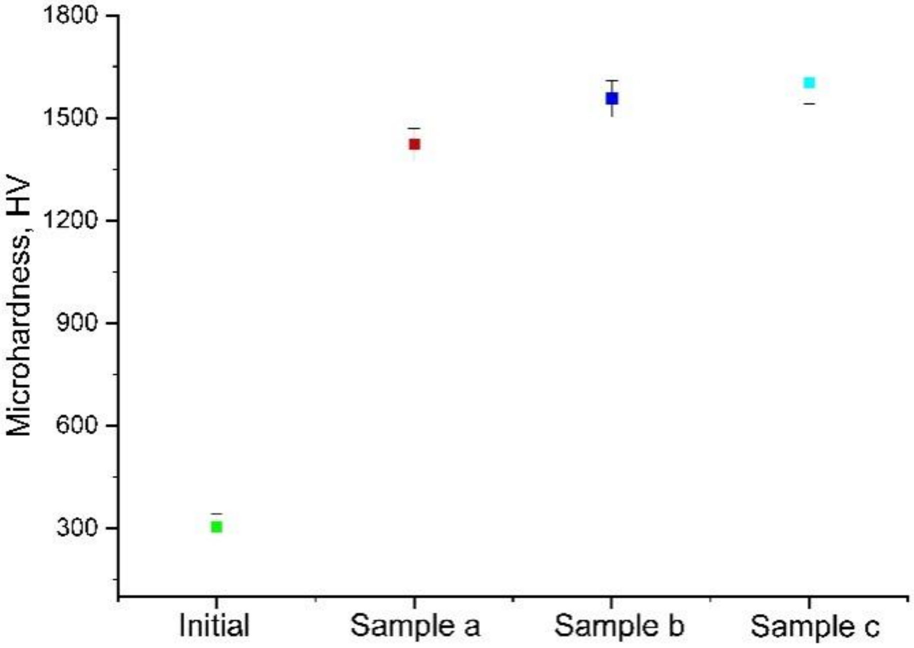

Figure 3. Comparison of microhardness of the original material and ZrCN coatings obtained by the HVOF method.

Figure 3 shows the microhardness (HV) values of the original material and the coatings (a, b, c) obtained by the HVOF method at different oxygen pressures. It is evident that coating application leads to a sharp increase in microhardness compared to the initial state, and the differences between the samples reflect the influence of the spraying conditions on the formation of the coating structure.

The microhardness of the original sample is approximately 304 HV, whereas after coating application it increases to 1423 HV (a), 1557 HV (b), and 1604 HV (c). Thus, the increase in microhardness after HVOF spraying reaches more than 4-5 times, indicating the formation of a dense, hardened coating structure with high resistance to plastic deformation.

A comparison between the samples shows that coating c exhibits the highest microhardness, exceeding the value for coating b by approximately 4-5% and for coating a by 14%. Coating b, on the other hand, exhibits intermediate values, exceeding a by approximately 8-9%. These differences indicate a significant influence of the HVOF process parameters on the structural state of the coating.

Small error values indicate good measurement reproducibility and coating thickness uniformity. For all samples, the spread of values remains relatively small, indicating the stability of the spraying process under the selected conditions.

It is important to note that the observed trend in microhardness fully correlates with previously obtained data on adhesion strength: sample c, which exhibits maximum adhesion, also exhibits the highest microhardness. This indicates the formation of the densest and highest-quality coating structure under the appropriate spraying parameters. Thus, optimization of HVOF modes allows for simultaneous improvement of both the mechanical and adhesion properties of the coating.

In practical terms, the obtained results confirm that controlling the HVOF process parameters is an effective tool for increasing the microhardness of coatings without changing their chemical composition. The most promising mode is the mode corresponding to sample c, which ensures maximum microhardness values and, consequently, potentially improved wear resistance and durability of the coating.

4. Conclusions

The study found that HVOF parameters have a significant impact on the structure and mechanical properties of zirconium carbonitride (ZrCN) coatings applied to a U8G steel substrate. It was found that increasing oxygen pressure during HVOF spraying from 3.3 to 3.7 bar positively impacts the mechanical properties of ZrCN coatings. With increasing oxygen pressure, adhesion strength increases from sample b to sample c, where the maximum value is approximately 16.5 MPa. A similar trend was observed for microhardness: with increasing oxygen pressure, its value increased from ~1420 HV (sample a) to ~1600 HV (sample c).

These results are related to the fact that increasing oxygen pressure promotes more intense combustion of the fuel mixture, increasing the temperature and velocity of the gas flow, which ensures better heating and acceleration of the powder particles. As a result, the particles deform more effectively upon impact with the substrate, forming a denser coating with reduced porosity and improved adhesion to the substrate. Thus, in the studied range, an oxygen pressure of 3.7 bar is optimal.

A direct correlation was established between the microhardness and adhesion strength of the coatings, indicating the formation of a denser and more uniform microstructure under optimal HVOF spraying conditions. Improved properties are attributed to reduced porosity, improved particle flattening, and improved coating-substrate interface quality.

Thus, optimizing the HVOF process parameters is an effective tool for managing the performance characteristics of ZrCN coatings. The obtained results confirm the potential for their use in increasing the wear resistance and durability of machine parts and tools operating under intense mechanical and thermal loads. Further tribological and corrosion testing, as well as studies of the long-term stability of the coatings under real-world operating conditions, are advisable.

References

1. Yao, S.H.; Su, Y.L.; Kao, W.H.; Cheng, K.W., Structural and Tribological Properties of ZrCN Coatings. *Materials Letters,* **2005**, *vol. 59*, pp. 3230–3233.
2. Kudapa, S.; Narasimhan, K.; Boppana, P.; Russel, W.C., Deposition and Characterization of Zr-Based Coatings. *Surface and Coatings Technology,* **1999**, *vol. 120–121*, pp. 259–266.
3. Grigore, E.; Ruset, C.; Li, X.; Dong, H., Properties of ZrCN Coatings. *Surface and Coatings Technology,* **2010**, *vol. 204*, pp. 1889–1893.
4. Balaceanu, M.; Petreus, T.; Braic, V.; Zoita, C.N.; Vladescu, A.; Cotrutz, C.E.; Braic, M., Characterization of ZrCN Coatings. *Surface and Coatings Technology,* **2010**, *vol. 204*, pp. 2046–2050.
5. Rie, K.-T.; Wöhle, J., Zr-Based Hard Coatings. *Surface and Coatings Technology,* **1999**, *vol. 112*, pp. 226–231.
6. Gu, J.-D.; Chen, P.-L., Characterization of Zirconium Carbonitride Coatings. *Surface and Coatings Technology,* **2006**, *vol. 200*, pp. 3341–3345.
7. Larijani, M.M.; Zanjanbar, M.B.; Majdabadi, A., Mechanical Properties of ZrCN Coatings. *Journal of Alloys and Compounds,* **2010**, *vol. 492*, pp. 735–739.
8. Vepřek, S.; Nesládek, P.; Niederhofer, A.; Glatz, F.; Jílek, M.; Šíma, M., Superhard Nanocomposite Coatings. *Surface and Coatings Technology,* **1998**, *vol. 108–109*, pp. 138–147.
9. Musil, J.; Poláková, H., Hard Nanocomposite Coatings. *Surface and Coatings Technology,* **2000**, *vol. 99*, pp. 127–131.
10. Carvalho, S.; Ribeiro, E.; Rebouta, L.; Tavares, C.; Mendonça, J.P.; Caetano Monteiro, A.; Carvalho, N.J.M.; De Hosson, J.Th.M.; Cavaleiro, A., Mechanical Properties of ZrCN Coatings. *Surface and Coatings Technology,* **2004**, *vol. 177–178*, pp. 459–468.
11. Field, S.K.; Jarratt, M.; Teer, D.G., Tribological Behaviour of Hard Coatings. *Tribology International,* **2004**, *vol. 37*, pp. 949–956.
12. Zehnder, T.; Patscheider, J., Structural Properties of ZrCN Coatings. *Surface and Coatings Technology,* **2000**, *vol. 138*, pp. 133–139.
13. Soldán, J.; Neidhardt, J.; Sartory, B.; Kaindl, R.; Čerstvý, R.; Mayrhofer, P.H.; Tessadri, R.; Polcik, P.; Lechthaler, M.; Mitterer, C., Multilayer Hard Coatings. *Surface and Coatings Technology*, **2008**, *vol. 202*, pp. 3555–3562.
14. Martínez-Martínez, D.; Sánchez-López, J.C.; Rojas, T.C.; Fernández, A.; Eaton, P.; Belin, M., Microstructural Analysis of Coatings. *Thin Solid Films*, **2005**, *vol. 472*, pp. 64–71.
15. Karlsson, L.; Hultman, L.; Johansson, M.P.; Sundgren, J.E.; Ljungcrantz, H., Growth of ZrCN Coatings. *Surface and Coatings Technology*, **2000**, *vol. 126*, pp. 1–14.
16. Bull, S.J.; Bhat, D.G.; Staia, M.H., Nanostructured Hard Coatings. *Surface and Coatings Technology*, **2003**, *vol. 163–164*, pp. 499–506.
17. Bull, S.J.; Bhat, D.G.; Staia, M.H., Mechanical Behaviour of Hard Coatings. *Surface and Coatings Technology*, **2003**, *vol. 165*, pp. 507–513.
18. Polcar, T.; Novák, R.; Široký, P., Tribological Performance of Coatings. *Wear*, **2006**, *vol. 260*, pp. 40–49.
19. Rebelo de Figueiredo, M.; Neidhardt, J.; Kaindl, R.; Reiter, A.; Tessadri, R.; Mitterer, C., Wear Behaviour of Hard Coatings. *Wear*, **2008**, *vol. 265*, pp. 525–533.

20. Balaceanu, M.; Braic, M.; Braic, V.; Pavelescu, G., Properties of Zr-Based Coatings. *Surface and Coatings Technology*, **2005**, *vol. 200*, pp. 1084–1089.
21. Kuznetsova, T.A.; et al. Effect of Atmosphere During Deposition on the Morphology, Mechanical Properties and Microfriction of Zr-Based Coatings. In *Advanced Materials Modelling for Mechanical, Medical and Biological Applications*; Springer: Cham, Switzerland, **2021**, *vol. 155*, pp. 271–319.
22. Huang, S.H.; et al. Microstructure and Mechanical Properties Evaluation of Cathodic Arc Deposited CrCN/ZrCN Multilayer Coatings. *Journal of Alloys and Compounds*, **2019**, *vol. 803*, pp. 1005–1015.
23. Mueller, R.; et al. Nanoparticle Synthesis and Deposition: Processing Aspects. *Powder Technology*, **2003**, *vol. 140*, pp. 40–48.
24. Mueller, R.; et al. Gas-Phase Synthesis of Nanoparticles. *Journal of Nanoparticle Research*, **2004**, *vol. 6*, pp. 39–50.
25. Wegner, K.; Pratsinis, S.E., Scale-Up of Nanoparticle Synthesis in Diffusion Flame Reactors. *Chemical Engineering Science*, **2003**, *vol. 58*, pp. 4581–4589.
26. Xun, Y.; et al. Processing of Nanostructured Coatings by HVOF Spraying. *Surface and Coatings Technology*, **2004**, *vol. 179*, pp. 262–268.
27. He, J.; Schoenung, J.M., Nanostructured Coatings by Thermal Spraying. *Materials Science and Engineering A*, **2002**, *vol. 336*, pp. 274–319.
28. Ajdelsztajn, L.; et al. Processing and Properties of Nanostructured Coatings. *Surface and Coatings Technology*, **2002**, **vol. 151–152**, pp. 1–7.
29. Anusha, K.; Routara, B.C.; Guha, S., A Review on High-Velocity Oxy-Fuel (HVOF) Coating Technique. *Journal of the Institution of Engineers (India): Series D*, **2023**, *vol. 104*, pp. 831–848.
30. Kurbanbekov, S.R.; et al. Effect of HVOF Spraying Parameters on the Structural-Phase Composition and Mechanical Properties of ZrCN Coating. *Bulletin of the Karaganda University. Physics Series*, **2025**, no. 3, pp. 31–40.
31. Harrison, R. Processing and Characterisation of ZrCxNy Ceramics as a Function of Stoichiometry via Carbothermic Reduction-Nitridation. PhD Thesis, Imperial College London, London, United Kingdom, **2015**.