Theoretical investigation of the deposition process of a tungsten carbide-based composite coating on a Ni-Cr-Fe alloy layer

Rakhimberdi Nurullaev
Almalyk State Technical Institute

Abstract: *This paper presents a theoretical investigation of the formation of a tungsten carbide (WC)-based composite coating deposited onto an intermediate Ni-Cr-Fe alloy layer on steel components. The physical mechanisms governing heat transfer, elemental diffusion, particle interaction, and interfacial bonding within the multilayer coating system are analyzed. Mathematical models based on the Fourier heat conduction equation, Fick's laws of diffusion, the Arrhenius equation, and thermoelastic stress theory are proposed to describe the coating formation process. The role of the Ni-Cr-Fe alloy as an intermediate bonding layer and the contribution of the WC-based composite coating to improving wear resistance are theoretically discussed. The proposed approach provides a theoretical foundation for further optimization of coating composition and processing parameters.*
Keywords: *Ni-Cr-Fe alloy, tungsten carbide, WC-Co, composite coating, multilayer coating, diffusion, heat transfer, adhesion, residual stress, mathematical modeling*

1. INTRODUCTION

The improvement of wear resistance and service life of machine components remains one of the important challenges in modern mechanical engineering. Components operating under friction, abrasive wear, high contact loads, and elevated temperatures are subjected to intensive surface degradation. Surface engineering technologies, particularly the formation of wear-resistant composite coatings, provide effective solutions to these problems. [1, 2, 3]

Tungsten carbide (WC) is widely used in protective coatings because of its high hardness and excellent resistance to abrasive wear. However, achieving reliable bonding between WC-based coatings and steel substrates remains a technological challenge. Differences in thermal and mechanical properties between the coating and substrate may result in residual stresses, microcracking, and interfacial separation. [1, 2, 3]

The use of an intermediate Ni-Cr-Fe alloy layer represents a potential approach to improving the structural compatibility of the coating system. This layer can act as a transition zone between the steel substrate and the WC-based composite coating, contributing to interfacial bonding and the distribution of thermal and mechanical stresses. [1, 2, 3]

The formation of such multilayer systems involves several interconnected processes, including heat transfer, elemental diffusion, particle consolidation, and phase interactions. Understanding these mechanisms is essential for establishing scientifically justified coating parameters. [4]

The objective of this study is to develop a theoretical framework describing the formation of a WC-based composite coating on a Ni-Cr-Fe alloy layer and to establish mathematical relationships governing the thermal, diffusion, and mechanical characteristics of the multilayer system. [1, 2, 3]

2. MATERIALS AND METHODS

2.1. Structural concept of the multilayer coating system

The development of wear-resistant coatings based on tungsten carbide requires consideration of the physical, chemical and mechanical properties of both the substrate material and the deposited coating. In this study, a multilayer coating system consisting of a steel substrate, a Ni-Cr-Fe alloy intermediate layer and a tungsten carbide-based composite outer layer is considered.

The main purpose of introducing the Ni-Cr-Fe intermediate layer is to improve the compatibility between the steel substrate and the hard WC-based coating. Direct deposition of a ceramic-rich hard coating onto a steel surface may result in significant differences in thermal expansion, elastic properties and interfacial behavior. These differences can contribute to residual stresses, cracking and partial separation of the coating during cooling or operation. [1, 2, 3]

The intermediate Ni-Cr-Fe alloy layer serves as a transition zone between the steel substrate and the WC-based composite coating. Its metallic nature provides a more gradual transition in mechanical and thermal properties, while its composition may promote interfacial bonding and improve the structural integrity of the coating system. [1, 2, 3]

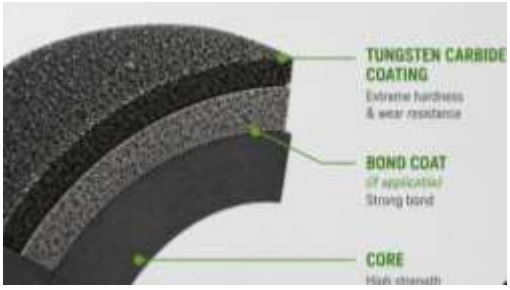


Figure 1. Schematic structure of the multilayer coating system consisting of a steel substrate, Ni-Cr-Fe intermediate layer and WC-based composite coating

2.2. Characteristics of the coating materials

Tungsten carbide is widely used in wear-resistant engineering applications because of its high hardness, good compressive strength and resistance to abrasive wear. Its properties make it suitable for protecting machine components operating under intensive friction and contact loading.

However, tungsten carbide particles alone do not always provide sufficient structural integrity in a deposited coating. Therefore, a metallic binder is generally required to connect the carbide particles and improve the cohesion of the coating. Depending on the selected technology, cobalt-, nickel- or nickel-based alloy binders may be used. [1, 2, 3]

The Ni-Cr-Fe intermediate layer is considered an important component of the proposed coating system. Nickel contributes to the metallic continuity and toughness of the layer, chromium can improve oxidation and corrosion resistance, while iron provides compatibility with steel-based substrates. The actual behavior depends on the chemical composition, phase constitution and deposition conditions.

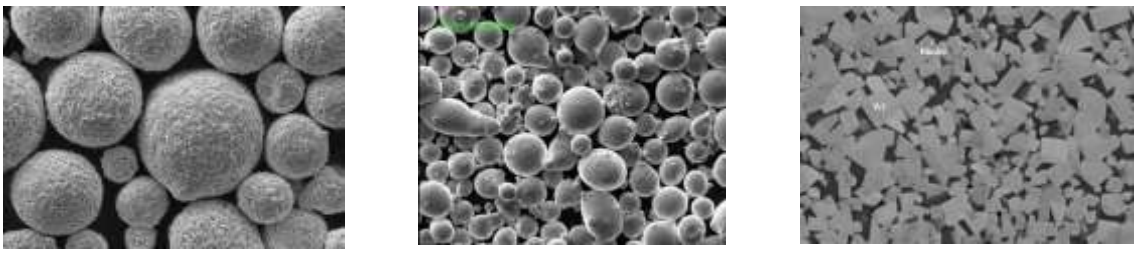


Figure 2. Representative microstructural features of tungsten carbide-based composite materials and Ni-Cr-Fe alloy powders

2.3. Theoretical investigation of heat transfer

Heat transfer is one of the main factors influencing the formation of multilayer coatings. During deposition, the substrate, intermediate layer and WC-based composite coating are exposed to thermal effects. The intensity and duration of heating determine the temperature distribution within the coating system.

The thermal behavior of the multilayer structure depends on the thermal conductivity, density, specific heat capacity and thickness of each layer. Since these parameters differ between steel, Ni-

Cr-Fe alloy and WC-based composite materials, the temperature distribution is not necessarily uniform throughout the system.

The steel substrate acts as the main heat-absorbing body. The Ni-Cr-Fe intermediate layer influences heat transfer between the substrate and the outer coating. The WC-based composite layer has its own thermal response, which is determined by the volume fraction of carbide particles, metallic binder content and microstructural characteristics.

During heating and subsequent cooling, temperature gradients may develop between the individual layers. These gradients are important because they can affect the formation of residual stresses and the integrity of the coating interface. [5, 6]

3. RESULTS AND DISCUSSION

3.1. Thermal behavior of the multilayer coating system

The formation of a tungsten carbide-based composite coating on a Ni-Cr-Fe alloy intermediate layer is accompanied by complex thermal processes. The temperature conditions during coating deposition have a significant influence on the structural development, interfacial interaction and final properties of the multilayer system.

The proposed coating structure consists of three main components: a steel substrate, a Ni-Cr-Fe intermediate layer and an outer WC-based composite coating. Each component has different thermal characteristics, including thermal conductivity, heat capacity and thermal expansion behavior. Consequently, the distribution of temperature throughout the multilayer structure is determined by the combined thermal response of these materials.

The steel substrate acts as the main heat-absorbing element, while the Ni-Cr-Fe intermediate layer provides a transition between the substrate and the hard composite coating. The outer WC-based layer responds to thermal input according to its carbide content, metallic binder composition and microstructural characteristics.

During the heating stage, heat is transferred from the processing zone into the coating and substrate. The intensity of heat transfer determines the temperature gradient across the individual layers. During subsequent cooling, the heat is gradually released into the surrounding environment. Differences in the cooling behavior of the materials may lead to non-uniform thermal contraction.

The presence of the Ni-Cr-Fe intermediate layer is important because it can reduce the abrupt transition between the thermal and mechanical properties of steel and the WC-based composite. However, its effectiveness depends on its chemical composition, thickness and structural condition.

Therefore, the selection of appropriate thermal processing conditions is essential for obtaining a uniform coating structure and reducing the risk of thermal cracking and interfacial separation. [4]

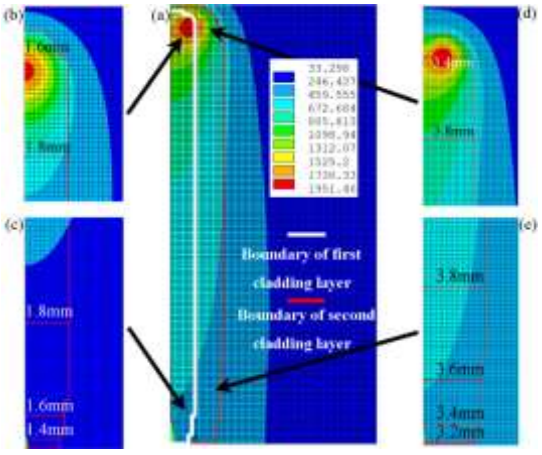


Figure 6. Schematic temperature distribution in the steel/Ni-Cr-Fe/WC multilayer coating system during thermal processing

3.2. Diffusion processes and formation of the interfacial transition zone

The interaction between the individual layers plays an important role in determining the adhesion and structural stability of the coating. During thermal processing, diffusion of chemical elements may occur across the interfaces, resulting in changes in local chemical composition and microstructure.

At the steel/Ni-Cr-Fe interface, the redistribution of iron, nickel and chromium may contribute to the formation of a diffusion-affected transition region. This region is important because it influences the continuity of the metallic bond between the substrate and intermediate layer.

At the Ni-Cr-Fe/WC interface, the interaction between the metallic alloy and tungsten carbide-based composite is more complex. The behavior of tungsten and carbon depends on the processing temperature, duration, binder composition and chemical stability of the carbide particles.

The formation of an appropriate interfacial transition zone can improve the structural connection between adjacent layers. A gradual change in chemical composition may contribute to better compatibility and reduce the probability of localized separation.

However, excessive thermal exposure may cause undesirable microstructural changes, including grain growth, carbide decomposition or the formation of brittle reaction products. Such changes can negatively affect the mechanical properties and reliability of the coating.

For this reason, the thermal processing conditions should be selected to ensure sufficient interfacial interaction while preserving the required structure of the WC-based composite.

3.3. Influence of WC content on the mechanical properties of the coating

The mechanical performance of tungsten carbide-based composite coatings is primarily determined by the carbide particle content, metallic binder characteristics and quality of the coating microstructure.

Tungsten carbide particles provide high hardness and resistance to abrasive wear. The metallic binder connects individual carbide particles and contributes to the structural integrity of the composite. Therefore, the balance between the hard carbide phase and the metallic matrix is an important factor in determining the overall mechanical behavior of the coating.

An increase in WC content generally leads to an increase in the proportion of hard reinforcing particles. This can improve hardness and resistance to abrasive wear. However, excessive carbide concentration may result in insufficient binder content, non-uniform particle distribution and increased susceptibility to crack formation.

The distribution of WC particles is also important. Uniform distribution promotes more consistent mechanical properties throughout the coating thickness. In contrast, particle agglomeration and local variations in binder concentration may create structural heterogeneity and localized stress concentrations.

The Ni-Cr-Fe intermediate layer contributes to the mechanical compatibility between the steel substrate and the hard outer coating. Its characteristics influence the transfer of mechanical loads between the layers and may affect the resistance of the coating system to interfacial failure.

Consequently, the optimum WC content should be selected by considering not only maximum hardness but also coating toughness, adhesion, porosity and wear resistance.

3.4. Residual stresses and structural stability of the coating

Residual stresses are among the important factors affecting the service performance of multilayer coatings. They may develop during deposition and cooling because of differences in thermal expansion, elastic properties and structural transformations of the individual materials.

The steel substrate, Ni-Cr-Fe intermediate layer and WC-based composite coating exhibit different responses to temperature changes. During cooling, each layer undergoes thermal contraction

according to its own material characteristics. Since the layers are connected, their deformation is mutually constrained, which may result in internal stresses.

The intermediate Ni-Cr-Fe layer can provide a transition between the relatively ductile steel substrate and the hard WC-based outer coating. This may improve the distribution of mechanical stresses across the interface. Nevertheless, the actual effectiveness of the intermediate layer depends on its thickness, composition, elastic properties and bonding quality.

High residual stresses may contribute to the development of microcracks, coating delamination and premature failure under operational loading. These effects become particularly important when machine components operate under repeated contact, friction and impact conditions.

3.5. General assessment of the coating formation process

The theoretical analysis demonstrates that the formation of a WC-based composite coating on a Ni-Cr-Fe intermediate layer is governed by the interaction of thermal, diffusion and mechanical processes.

The thermal conditions determine the heating and cooling behavior of the multilayer system. Diffusion and interfacial interactions influence the formation of transition zones, while the composition and microstructure of the WC-based composite determine its mechanical and Based on these considerations, the Ni-Cr-Fe intermediate layer should be regarded not merely as an additional coating layer but as an important structural component that influences the formation and performance of the entire multilayer system.

The proposed theoretical approach provides a basis for further numerical modeling and experimental validation of the coating formation process. In particular, future investigations should focus on determining the optimum intermediate-layer thickness, WC concentration and thermal processing conditions to achieve improved adhesion, hardness and resistance to wear.

4. CONCLUSION

The theoretical investigation of the formation of a tungsten carbide-based composite coating on a Ni-Cr-Fe alloy intermediate layer demonstrates the importance of considering the thermal, diffusion and mechanical characteristics of the multilayer system as interconnected phenomena.

The proposed steel/Ni-Cr-Fe/WC structure provides a material transition between the steel substrate and the hard WC-based outer coating. The Ni-Cr-Fe intermediate layer is expected to contribute to improved interfacial compatibility and to reduce the abrupt differences in material properties between the substrate and the composite coating.

The analysis of thermal behavior shows that temperature distribution within the multilayer system is influenced by the thermal conductivity, heat capacity and thickness of the individual layers. Non-uniform heating and cooling may lead to temperature gradients and residual stresses, which can affect the structural integrity of the coating.

The investigation of diffusion processes indicates that interfacial interactions between the steel substrate, Ni-Cr-Fe alloy and WC-based composite layer are important for the formation of transition zones. The development of these zones depends on the processing temperature, duration and chemical composition of the materials.

The mechanical performance of the composite coating is closely related to the tungsten carbide content, metallic binder characteristics, particle distribution and porosity. An appropriate balance between hardness and toughness is necessary to achieve reliable wear resistance and structural stability.

It is also established that the thickness and properties of the Ni-Cr-Fe intermediate layer should be considered together with the thermal processing conditions. Their combined influence determines the distribution of stresses and the quality of bonding between adjacent layers.

The obtained theoretical considerations provide a scientific basis for further numerical simulation and experimental investigation of multilayer WC-based coatings. Future research should focus on determining optimal deposition conditions, evaluating the microstructure of the interfaces, measuring microhardness and adhesion strength, and investigating the wear resistance of the developed coating system. [1, 2, 3]

References

1. Torkashvand K., Joshi S., Gupta M. Advances in Thermally Sprayed WC-Based Wear-Resistant Coatings: Co-free Binders, Processing Routes and Tribological Behavior. Journal of Thermal Spray Technology. 2022;31:342–377. https://doi.org/10.1007/s11666-022-01358-4.
2. Ji S., Li J., Wang S., Zhang C., Wang Y., Zhang T., et al. HVOF-sprayed tungsten carbide cermet coatings on metal substrates: An overview. International Journal of Applied Ceramic Technology. 2026;23:e70112. https://doi.org/10.1111/ijac.70112.
3. Tiwari A., Seman S., Singh G., Jayaganthan R. Nanocrystalline Cermet Coatings for Erosion–Corrosion Protection. Coatings. 2019;9(6):400. https://doi.org/10.3390/coatings9060400.
4. Lu S.-P., Kwon O.-Y. Microstructure and bonding strength of WC reinforced Ni-base alloy brazed composite coating. Surface and Coatings Technology. 2002;153(1):40–48. https://doi.org/10.1016/S0257-8972(01)01555-9.
5. Abubakar A.A., Arif A.F.M., Al-Athel K.S., Akhtar S.S., Mostaghimi J. Modeling Residual Stress Development in Thermal Spray Coatings: Current Status and Way Forward. Journal of Thermal Spray Technology. 2017;26(6):1115–1145. https://doi.org/10.1007/s11666-017-0590-1.
6. Martínez-García J., Martínez-García V., Killinger A. Multi-Scale Thermo-Mechanical Model Simulation of Residual Stress in Atmospheric Plasma Spray Process. Coatings. 2024;14(12):1547. https://doi.org/10.3390/coatings14121547.
7. Ang A.S.M., Berndt C.C. A review of testing methods for thermal spray coatings. International Materials Reviews. 2014;59(4):179–223. https://doi.org/10.1179/1743280414Y.0000000029