

Tribological Performance and Microstructural Characterization of Microwave-Processed Ni-Cr/WC-Co-Cr Composite Cladding on Stainless Steel 304

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Abstract:

Surface degradation caused by wear is one of the major challenges limiting the service life of stainless steel (SS-304) components operating under severe engineering conditions. To overcome this limitation, the present study investigates the development and tribological performance of Ni-Cr reinforced with 20 wt.% WC-Co-Cr composite cladding deposited on SS-304 substrate using the microwave hybrid heating (MHH) technique. Microwave cladding was carried out in a domestic multimode microwave applicator operating at 2.45 GHz with a power rating of 900 W, enabling rapid volumetric heating and strong metallurgical bonding between the clad and substrate. The developed cladding was characterized using scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), X-ray diffraction (XRD), and Vickers microhardness testing to evaluate its microstructure, elemental distribution, phase formation, and mechanical properties. The tribological performance was assessed through dry sliding wear tests using a pin-on-disc tribometer following ASTM G99 standards. Microstructural characterization revealed a dense, homogeneous, and defect-minimized clad layer with uniform dispersion of WC-Co-Cr reinforcement within the Ni-Cr matrix. XRD confirmed the presence of hard carbide phases responsible for enhanced mechanical performance. The composite cladding exhibited a significant increase in microhardness, reaching approximately 660 ± 12 HV, compared with 230 ± 10 HV for the SS-304 substrate. Sliding wear results demonstrated substantially lower cumulative weight loss and wear coefficient for the clad specimens, indicating nearly fourfold improvement in wear resistance over the uncoated substrate. SEM analysis of worn surfaces confirmed that the composite cladding effectively minimized severe abrasion, ploughing, and plastic deformation. The study demonstrates that microwave-assisted Ni-Cr/WC-Co-Cr composite cladding is an efficient surface engineering approach for significantly enhancing the tribological performance and service life of SS-304 components intended for demanding industrial applications.

Keywords: Microwave hybrid heating (MHH), Ni-Cr composite cladding, WC-Co-Cr reinforcement, Stainless steel 304, Tribological performance, Sliding wear resistance

1. Introduction

Stainless steel 304 (SS-304) is one of the most extensively used austenitic stainless steels because of its excellent corrosion resistance, good weldability, adequate mechanical strength, and cost-effectiveness. Owing to these characteristics, it is widely employed in chemical processing plants, food processing equipment, heat exchangers, marine components, power generation systems, automotive exhaust systems, and petrochemical industries. Despite these advantages, SS-304 suffers from relatively low surface hardness and poor wear resistance under severe sliding, abrasive, and high-temperature operating conditions. Continuous friction and mechanical loading often result in excessive material removal, surface deformation, and premature component failure, thereby increasing maintenance

costs and reducing service life. Consequently, improving the surface properties of SS-304 without affecting its desirable bulk characteristics has become an important area of research in surface engineering (Thostenson & Chou, 1999; Gupta & Sharma, 2011).

Surface modification technologies have emerged as effective approaches to enhance the tribological and mechanical performance of engineering materials. Various techniques such as thermal spraying, laser cladding, plasma transferred arc (PTA) cladding, tungsten inert gas (TIG) cladding, and high-velocity oxy-fuel (HVOF) spraying have been successfully employed to deposit wear-resistant coatings on metallic substrates (Davis, 2004; Zhang et al., 2002; Wang et al., 2012). These techniques improve hardness, wear resistance, and corrosion behaviour by producing protective surface layers containing hard ceramic or carbide reinforcements. However, conventional cladding processes also possess certain limitations, including excessive heat input, high dilution of coating materials, residual stresses, distortion of the substrate, porosity, and expensive processing equipment. These shortcomings have motivated researchers to explore alternative coating technologies that are more energy-efficient and capable of producing dense metallurgically bonded coatings with minimal thermal damage (Gupta & Sharma, 2012; Sharma & Gupta, 2012).

Among the emerging surface engineering techniques, microwave hybrid heating (MHH) has attracted significant attention because of its unique volumetric heating mechanism and superior energy efficiency. Unlike conventional heating methods, where heat is transferred from the surface to the interior through conduction, microwave processing generates heat directly within the material by dielectric interaction with electromagnetic waves. This internal heating mechanism produces uniform temperature distribution, minimizes thermal gradients, reduces processing time, and enhances microstructural homogeneity (Mishra & Sharma, 2015; Oghbaei & Mirzaee, 2010). Since bulk metallic materials exhibit poor microwave absorption at room temperature, microwave hybrid heating employs susceptors such as charcoal to initiate heating and subsequently transfer heat to the metallic specimen. This hybrid approach enables successful processing of metallic materials, including joining, sintering, glazing, and cladding applications (Srinath et al., 2011; Sharma et al., 2001).

Microwave cladding has recently emerged as a promising surface modification process capable of producing dense, crack-free coatings with excellent metallurgical bonding between the coating and substrate. During microwave cladding, powder feedstock melts under hybrid microwave heating and solidifies rapidly to form a well-bonded coating possessing improved mechanical and tribological characteristics. Compared with conventional surface engineering methods, microwave cladding offers several advantages, including lower energy consumption, shorter processing time, refined microstructure, reduced porosity, enhanced diffusion across the interface, and improved coating integrity (Gupta et al., 2011; Zafar & Sharma, 2017). These advantages make microwave cladding particularly attractive for manufacturing wear-resistant surfaces on engineering components subjected to severe service environments.

Nickel-based alloys are among the most preferred matrix materials for protective coatings because of their excellent corrosion resistance, oxidation resistance, thermal stability, and good compatibility with steel substrates. Among these alloys, Ni-Cr has been extensively utilized due to its superior high-temperature strength, excellent oxidation resistance, and ability to form stable metallurgical bonds with ferrous substrates (Sidhu et al., 2005; Zafar & Sharma, 2017). Nevertheless, the hardness and wear resistance of pure Ni-Cr coatings are often insufficient for highly demanding tribological applications. Therefore, reinforcing the Ni-Cr matrix with hard ceramic particles has become an effective strategy for enhancing coating performance.

Tungsten carbide-cobalt-chromium (WC-Co-Cr) is one of the most widely used cermet reinforcement materials because of its exceptional hardness, excellent wear resistance, high fracture toughness, and superior thermal stability. The presence of tungsten carbide significantly increases resistance to abrasion and erosion, while cobalt improves toughness and chromium enhances corrosion and oxidation resistance. Consequently, WC-Co-Cr-reinforced coatings have found widespread applications in aerospace, mining, oil and gas, marine, power generation, and heavy manufacturing industries where components are exposed to severe wear conditions (Murthy et al., 2001; Vasudev et al., 2019). Numerous studies have demonstrated that carbide-reinforced coatings exhibit significantly lower wear rates than unreinforced coatings due to the formation of hard carbide phases that effectively resist plastic deformation and material removal during sliding contact (Mateos et al., 2000; Wang et al., 2012).

Previous investigations have demonstrated the potential of microwave processing for improving coating properties. Gupta and Sharma (2011) reported enhanced sliding wear resistance of microwave-developed WC10Co2Ni coatings owing to improved densification and reduced porosity. Similarly, Zafar and Sharma (2017) observed that microwave post-processing of nickel-based coatings considerably improved microstructure, fracture toughness, and wear

resistance through elimination of microcracks and improved splat cohesion. Bansal et al. (2014) further demonstrated that microwave hybrid heating successfully produced metallurgically bonded stainless-steel joints exhibiting superior mechanical properties. More recently, studies involving microwave-cladded Inconel-625 coatings have reported significant improvements in hardness and wear resistance due to the formation of Laves phases and carbide precipitates within the clad layer (Singh et al., 2024).

Despite these advancements, the application of WC-Co-Cr reinforcement in Ni-Cr matrix coatings developed through microwave hybrid heating remains relatively unexplored. Most reported investigations involving WC-Co-Cr coatings have focused on thermal spraying, HVOF, laser cladding, or TIG cladding processes, where high heat input may cause undesirable dilution, residual stresses, and microstructural deterioration (Mateos et al., 2000; Wang et al., 2012). Limited information is available regarding the microstructural evolution, phase formation, hardness enhancement, and tribological behaviour of Ni-Cr/WC-Co-Cr composite claddings fabricated using microwave hybrid heating. Furthermore, comprehensive investigations correlating reinforcement distribution, carbide formation, and wear mechanisms with coating performance are scarce.

In view of these research gaps, the present study focuses on the development of Ni-Cr reinforced with WC-Co-Cr composite cladding on SS-304 substrate using microwave hybrid heating. The microwave cladding process is expected to produce dense metallurgically bonded coatings with uniform reinforcement distribution and minimal porosity. Detailed characterization using scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), X-ray diffraction (XRD), and Vickers microhardness testing is carried out to evaluate the microstructural and mechanical characteristics of the developed coatings. Furthermore, the tribological performance is assessed through dry sliding wear testing following ASTM G99 standards, and the wear mechanisms are investigated using SEM analysis of worn surfaces. The findings of this study are expected to contribute to the development of durable, wear-resistant surface coatings for stainless steel components employed in demanding industrial applications, while also demonstrating the potential of microwave hybrid heating as an energy-efficient and sustainable surface engineering technology.

2. Literature Review

Surface engineering has become one of the most important research areas for improving the performance and service life of engineering components operating under severe mechanical and thermal environments. Stainless steel 304 (SS-304) is extensively used in industries because of its excellent corrosion resistance, weldability, and mechanical strength. However, its relatively low hardness and poor wear resistance limit its application under abrasive and sliding conditions. Consequently, researchers have focused on developing protective surface coatings using advanced cladding and thermal processing techniques to enhance the tribological performance of stainless steel while retaining its desirable bulk properties (Davis, 2004; Thostenson & Chou, 1999).

Among the available surface modification techniques, thermal spraying, laser cladding, TIG cladding, plasma transferred arc (PTA) cladding, and high-velocity oxy-fuel (HVOF) spraying have been widely investigated for depositing wear-resistant coatings. These techniques improve the surface hardness and wear resistance by introducing hard ceramic particles or carbide reinforcements into metallic matrices. Nevertheless, conventional coating processes often suffer from drawbacks such as excessive heat input, dilution of the coating material, residual stresses, porosity, microcracking, and high processing costs. These limitations have encouraged researchers to investigate alternative processing routes capable of producing dense coatings with superior metallurgical bonding and lower energy consumption (Mateos et al., 2000; Wang et al., 2012).

Microwave materials processing has emerged as a promising alternative because of its unique volumetric heating mechanism. Unlike conventional heating, microwave energy generates heat directly within the material through dielectric interactions, resulting in rapid and uniform heating, shorter processing times, reduced energy consumption, and improved microstructural homogeneity. Microwave hybrid heating (MHH), which employs susceptors such as charcoal to initiate heating of metallic materials, has further expanded the application of microwave processing to joining, sintering, glazing, and cladding of engineering materials (Mishra & Sharma, 2015; Oghbaei & Mirzaee, 2010). These advantages have made microwave-assisted surface engineering an attractive research area for producing high-performance coatings.

One of the earliest studies on microwave post-processing of coatings was conducted by Zafar and Sharma (2017), who investigated nickel-based flame-sprayed coatings subjected to microwave hybrid heating. Their study demonstrated that microwave treatment effectively eliminated microcracks and microporosity, resulting in a more homogeneous microstructure. The improved coating exhibited enhanced fracture toughness, reduced surface roughness, and significantly improved sliding wear resistance compared with the as-sprayed coating. The authors attributed these improvements to improved splat cohesion and densification during microwave heating.

Microwave processing has also been successfully applied to nickel-based superalloy coatings. Bansal et al. (2014) developed Inconel 718 cladding using microwave hybrid heating and subsequently performed different heat treatment conditions. Microstructural characterization revealed the presence of strengthening precipitates and Laves phases, while appropriate heat treatment significantly improved the hardness of the clad. Their work demonstrated that microwave cladding can produce dense metallurgically bonded coatings with superior mechanical properties suitable for high-temperature engineering applications.

Several researchers have investigated the influence of post-processing treatments on nickel-based coatings produced by thermal spraying. Gupta et al. (2011) examined HVOF-sprayed NiCrWBSi coatings subjected to carburizing flame and argon heat treatment. Their results indicated that heat treatment reduced porosity, eliminated lamellar structures, and improved corrosion resistance in sodium chloride solution. The study confirmed that microstructural refinement through post-processing plays a significant role in enhancing coating performance.

The incorporation of carbide reinforcements has received considerable attention because of their exceptional hardness and wear resistance. Murthy et al. (2001) investigated WC-Co-Cr coatings deposited by HVOF and detonation gun spraying and reported excellent erosion resistance compared with conventional coatings. Similarly, Mateos et al. (2000) demonstrated that laser remelting of plasma-sprayed WC coatings substantially enhanced wear resistance by reducing porosity and improving coating density. These investigations established WC-based composites as promising reinforcement materials for wear-resistant coatings.

The tribological behaviour of WC-Co-Cr coatings has also been investigated for machine tool applications. Vasudev et al. (2019) evaluated detonation gun-sprayed WC-Co-Cr coatings deposited on cast iron components used in lathe machine beds. Their experimental investigation revealed that WC-Co-Cr coatings exhibited significantly lower wear rates than uncoated cast iron under ASTM G99 pin-on-disc testing. SEM analysis showed only minor wear scars on coated specimens, demonstrating the effectiveness of carbide reinforcement in resisting abrasive wear.

Microwave plasma processing has also been explored for improving the surface properties of stainless steel. Srinath et al. (2011) fabricated nitride layers on biomedical stainless steel using microwave plasma treatment. The developed surface exhibited significantly improved hardness together with enhanced antibacterial behaviour. Their work highlighted the capability of microwave-assisted processing to modify metallic surfaces without adversely affecting substrate integrity.

Another important contribution was made by Bajpai et al. (2012), who investigated microwave hybrid heating for developing clad layers on stainless steel substrates. The microwave-processed coatings exhibited microhardness exceeding 1000 HV with very low porosity. Sliding wear experiments demonstrated considerably lower wear rates compared with the substrate, confirming the suitability of microwave cladding for wear-resistant engineering applications.

Research has also focused on microwave joining and metallurgical bonding of metallic materials. Gupta et al. (2011) successfully joined bulk copper using microwave hybrid heating and reported tensile strengths of approximately 164 MPa with satisfactory ductility. Likewise, Bansal et al. (2013) fabricated stainless steel joints through microwave hybrid heating and observed excellent fusion at the interface with minimal porosity. These investigations demonstrated the capability of microwave energy to produce high-quality metallurgical bonds.

Microwave cladding has also been employed for ceramic-reinforced composite coatings. Sharma and Gupta (2012) developed metal-ceramic composite claddings reinforced with chromium carbide using microwave heating. Microstructural analysis confirmed homogeneous reinforcement distribution and excellent bonding with the substrate, while hardness measurements revealed significant improvement compared with the base material. The enhanced hardness translated directly into improved wear resistance under sliding conditions.

The influence of ceramic reinforcement on high-temperature tribological performance has also attracted significant attention. Kamboj and Thakur (2023) investigated yttria-stabilized zirconia (YSZ)-reinforced Inconel 625 composite claddings fabricated by TIG cladding on SS-304. Their study demonstrated that increasing YSZ content significantly enhanced hardness and reduced wear through the formation of stable oxide phases such as Cr_2O_3 and ZrO_2 . The optimized coating exhibited excellent wear resistance at elevated temperatures, illustrating the beneficial role of ceramic reinforcement in improving tribological performance.

More recently, Singh et al. (2024) investigated microwave-cladded Inconel-625 coatings deposited on SS-304 substrates. SEM observations revealed dense, crack-free coatings possessing strong metallurgical bonding and extremely low porosity. The coating exhibited microhardness approximately twice that of the substrate owing to the formation of hard carbide and Laves phases. Dry sliding wear tests further demonstrated nearly threefold improvement in wear resistance compared with uncoated stainless steel, confirming the effectiveness of microwave cladding in enhancing surface performance.

Although substantial research has been conducted on microwave cladding, several knowledge gaps remain. Most published studies have focused on nickel alloys, Inconel-based coatings, chromium carbide reinforcements, or WC-based coatings developed using HVOF, laser cladding, or thermal spraying techniques. Comparatively fewer investigations have examined Ni-Cr matrix composite coatings reinforced with WC-Co-Cr using microwave hybrid heating. Furthermore, the combined influence of microwave processing on reinforcement distribution, carbide formation, microstructural refinement, hardness development, and tribological behaviour has not been comprehensively investigated. Limited studies have also correlated SEM observations, XRD phase evolution, and wear mechanisms with the enhanced performance of microwave-developed Ni-Cr/WC-Co-Cr composite coatings.

Therefore, the present research addresses these gaps by developing Ni-Cr reinforced with WC-Co-Cr composite cladding on SS-304 using microwave hybrid heating. The study systematically investigates the coating microstructure, elemental distribution, phase composition, hardness, and sliding wear behaviour using SEM, EDS, XRD, Vickers microhardness testing, and ASTM G99 pin-on-disc wear testing. The findings are expected to contribute to the development of energy-efficient, wear-resistant composite claddings for industrial applications requiring superior tribological performance under severe operating conditions.

3. Materials and Methodology

The present investigation focuses on the development of Ni-Cr reinforced with WC-Co-Cr composite cladding on AISI Stainless Steel 304 (SS-304) substrate using the microwave hybrid heating (MHH) technique. The methodology was designed to develop a dense, metallurgically bonded clad layer with enhanced hardness and tribological performance. The overall experimental procedure involved substrate preparation, powder selection, powder blending, microwave cladding, microstructural characterization, hardness evaluation, and tribological testing. The methodology adopted in this investigation is based on the experimental procedures described in the uploaded research work.

3.1 Selection of Substrate Material

AISI Stainless Steel 304 (SS-304) was selected as the substrate material because of its widespread industrial applications in heat exchangers, furnace components, petrochemical equipment, automotive exhaust systems, food processing machinery, and marine structures. The material possesses excellent corrosion resistance, good weldability, and satisfactory mechanical strength. However, its relatively low surface hardness and poor wear resistance under severe sliding conditions limit its service life in tribological applications. Therefore, SS-304 provides an ideal substrate for evaluating the effectiveness of microwave-deposited wear-resistant composite cladding.

The substrate plates were procured in the form of flat plates having dimensions of 50 mm × 50 mm × 5 mm. Prior to cladding, the substrate surfaces were ground using silicon carbide abrasive papers to remove oxide scales and surface contaminants. The specimens were subsequently cleaned using acetone to eliminate oil and grease before deposition of the cladding material. The chemical composition of the substrate was verified using an optical emission spectrometer to ensure conformity with standard SS-304 composition.

3.2 Selection of Cladding Materials

The matrix material selected for the composite cladding was Ni-Cr (80 wt.% Ni and 20 wt.% Cr) because of its excellent oxidation resistance, thermal stability, corrosion resistance, and ability to form strong metallurgical bonding with steel substrates. Nickel-based alloys also possess superior toughness and high-temperature mechanical properties, making them suitable for protective surface coatings. To improve the hardness and wear resistance of the coating, 20 wt.% WC-Co-Cr powder was selected as the reinforcement material. Tungsten carbide provides exceptional hardness and abrasion resistance, while cobalt improves toughness and chromium enhances oxidation and corrosion resistance. The combination of Ni-Cr matrix and WC-Co-Cr reinforcement was expected to produce a dense composite coating capable of resisting severe sliding wear. The reinforcement powder was blended with the Ni-Cr matrix using a ball milling process to achieve homogeneous mixing before deposition. The prepared powder mixture consisted of 80 wt.% Ni-Cr and 20 wt.% WC-Co-Cr, which served as the feedstock material for microwave cladding.

3.3 Microwave Hybrid Heating Setup

Microwave cladding was carried out using a domestic multimode microwave applicator operating at a frequency of 2.45 GHz with a maximum output power of 900 W. Since metallic materials do not effectively absorb microwave radiation at room temperature, the microwave hybrid heating technique was employed. In this process, charcoal powder was used as the microwave susceptor. Initially, charcoal absorbed microwave energy and generated heat, which was subsequently transferred to the powder mixture and substrate. An alumina ceramic plate was positioned between the charcoal and specimen to act as a separator and prevent contamination while ensuring efficient heat transfer.

The microwave hybrid heating arrangement promoted simultaneous internal and external heating, resulting in uniform melting of the powder layer and improved metallurgical bonding between the deposited coating and substrate. This approach significantly reduced thermal gradients and minimized residual stresses compared with conventional heating techniques.

3.4 Preparation of Composite Cladding

The cleaned SS-304 substrate was uniformly coated with the prepared Ni-Cr/WC-Co-Cr powder mixture. The powder-coated specimens were placed inside the microwave processing chamber using the microwave hybrid heating arrangement. The specimens were exposed to microwave irradiation for 900 seconds (15 minutes). During microwave exposure, the Ni-Cr matrix melted completely and encapsulated the WC-Co-Cr reinforcement particles, producing a dense composite coating. Visual inspection confirmed complete melting of the deposited powder and successful formation of the clad layer. Following microwave processing, the specimens were allowed to cool naturally under ambient conditions. The deposited cladding exhibited good surface integrity and strong metallurgical bonding with the substrate, making it suitable for further characterization and tribological evaluation.

3.5 Specimen Preparation for Characterization

After deposition, the clad specimens were sectioned for metallographic examination. Cross-sectional specimens were mounted and polished using progressively finer grades of silicon carbide papers followed by polishing with 1 μ m alumina paste to obtain a mirror-like surface finish. The polished specimens were etched where necessary to reveal the microstructure before microscopic examination. Additional cylindrical specimens were prepared for sliding wear testing according to ASTM G99 specifications.

3.6 Microstructural Characterization

The morphology and microstructure of the developed composite cladding were investigated using Scanning Electron Microscopy (SEM). SEM examination was performed to evaluate coating density, reinforcement distribution, grain morphology, interface characteristics, and coating integrity. The elemental composition of the clad was determined using Energy Dispersive Spectroscopy (EDS) attached to the SEM. EDS mapping was employed to confirm the

homogeneous distribution of Ni, Cr, W, Co, and Fe throughout the composite coating. Phase identification was carried out using X-ray Diffraction (XRD). The diffraction patterns were analyzed to identify the crystalline phases formed during microwave processing, including carbide phases responsible for hardness enhancement. XRD analysis also confirmed successful incorporation of WC-Co-Cr reinforcement within the Ni-Cr matrix.

3.7 Microhardness Measurement

The hardness of the developed composite cladding was measured using a Vickers microhardness tester. A load of 200 g was applied with a dwell time of 15 seconds. Hardness measurements were taken at regular intervals across the coating cross-section, and the average of multiple indentations was reported.

The hardness values obtained for the clad layer were compared with those of the uncoated SS-304 substrate to evaluate the strengthening effect produced by microwave cladding and carbide reinforcement. The increase in hardness was attributed to the presence of hard carbide phases, improved coating density, and strong metallurgical bonding produced during microwave hybrid heating.

3.8 Tribological Evaluation

The tribological performance of the composite coating was evaluated using a pin-on-disc tribometer in accordance with ASTM G99 standards. Cylindrical pin specimens having dimensions of 30 mm length and 6 mm diameter were machined from the coated samples.

The wear experiments were conducted under the following test conditions:

Applied load: 30 N

Disc diameter: 80 mm

Sliding duration: 5000 s

Before and after each wear test, the specimens were cleaned and weighed using a precision electronic balance to determine cumulative weight loss. The wear coefficient was calculated from the experimental data, and the performance of the composite coating was compared with that of the uncoated SS-304 substrate.

3.9 Analysis of Worn Surfaces

Following tribological testing, the worn surfaces of both coated and uncoated specimens were examined using SEM to identify the dominant wear mechanisms.

The SEM observations enabled identification of features such as abrasion grooves, ploughing marks, micro-cutting, pitting, and plastic deformation. These observations were correlated with weight-loss measurements and hardness values to explain the superior wear resistance exhibited by the microwave-developed Ni-Cr/WC-Co-Cr composite cladding.

3.10 Experimental Workflow

The experimental methodology adopted in the present investigation can be summarized as follows:

1. Selection and preparation of SS-304 substrate.
2. Preparation of Ni-Cr/WC-Co-Cr composite powder.
3. Ball milling for homogeneous powder mixing.

4. Microwave hybrid heating using charcoal susceptor and alumina separator.
5. Deposition of composite cladding under 2.45 GHz microwave irradiation for 900 s.
6. Metallographic specimen preparation.
7. Microstructural characterization using SEM, EDS, and XRD.
8. Microhardness measurement using Vickers hardness testing.
9. Dry sliding wear evaluation using ASTM G99 pin-on-disc testing.
10. SEM examination of worn surfaces to identify wear mechanisms.

The adopted methodology provides a systematic approach for evaluating the influence of microwave hybrid heating on the microstructure, hardness, and tribological performance of Ni-Cr reinforced WC-Co-Cr composite cladding developed on SS-304 substrate.

4. Results & Analysis

The present investigation evaluated the effectiveness of Ni-Cr reinforced with 20 wt.% WC-Co-Cr composite cladding deposited on SS-304 stainless steel using the microwave hybrid heating (MHH) technique. The developed cladding was characterized using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Diffraction (XRD), Vickers microhardness testing, and pin-on-disc wear testing. The experimental results demonstrate that microwave hybrid heating successfully produced a dense, metallurgically bonded composite coating with significantly improved hardness and wear resistance compared with the uncoated substrate. The detailed discussion of the experimental findings is presented in the following sections.

4.1 Morphological Characterization of Feedstock Powder

The morphology of the feedstock powder was first examined using SEM to understand the characteristics of the starting materials used for microwave cladding.

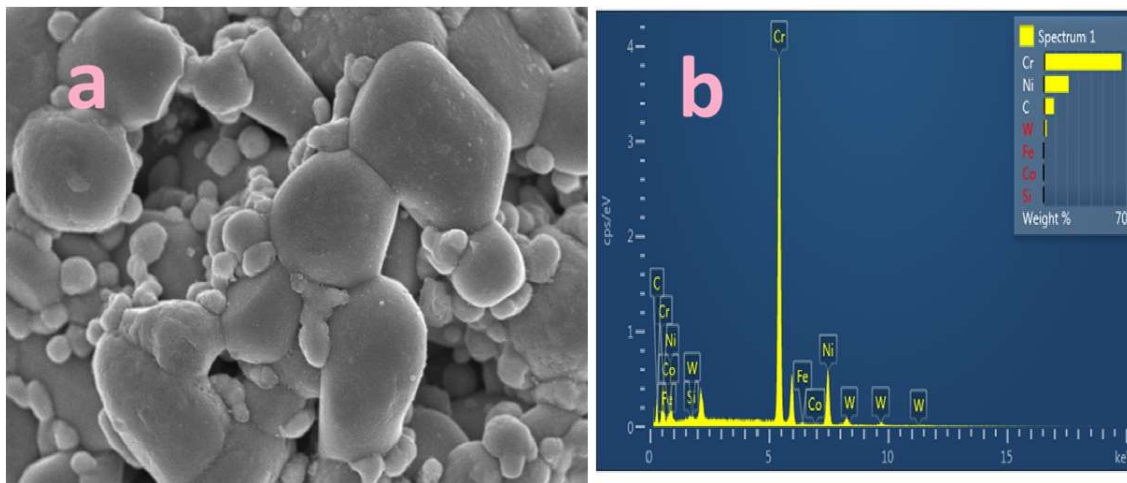


Figure 1 (a) : SEM/EDAX analysis of Ni-Cr +WC, Co, Cr cladding powder showing its morphology, Size of particles and elemental composition (wt %), (b) EDS of cladding powder.

The Ni-Cr powder exhibited predominantly spherical to irregular particles with relatively smooth surfaces. Such particle morphology is advantageous because it promotes improved packing density and melting behaviour during microwave processing. The irregular particles also provide greater contact area between individual particles, facilitating efficient diffusion during cladding.

The SEM and EDS of the cladding powder is presented in Figure.1. SEM analysis of the Ni-Cr/WC-Co-Cr (Figure 1a) blended powder revealed that the WC-Co-Cr reinforcement particles were uniformly distributed throughout the Ni-Cr matrix. The average particle size was approximately 40 μm , which is suitable for achieving homogeneous melting under microwave irradiation. EDS analysis confirmed the presence of nickel, chromium, tungsten, cobalt, oxygen, silicon, and carbon (Figure 1b). The dominant peaks corresponded to nickel and tungsten, indicating successful blending of the matrix and reinforcement powders.

The XRD pattern further confirmed the crystalline phases associated with Ni, Cr, WC, and Co-containing compounds. The absence of undesirable impurity phases indicated that the powder preparation procedure successfully maintained the chemical integrity of the constituent materials before microwave processing.

4.2 Microstructural Characteristics of Microwave Cladding

The cross-sectional SEM micrographs demonstrated that microwave hybrid heating successfully produced a continuous and dense composite clad on the SS-304 substrate. No major cracks, delamination, or coating separation were observed at the clad–substrate interface, indicating excellent metallurgical bonding.

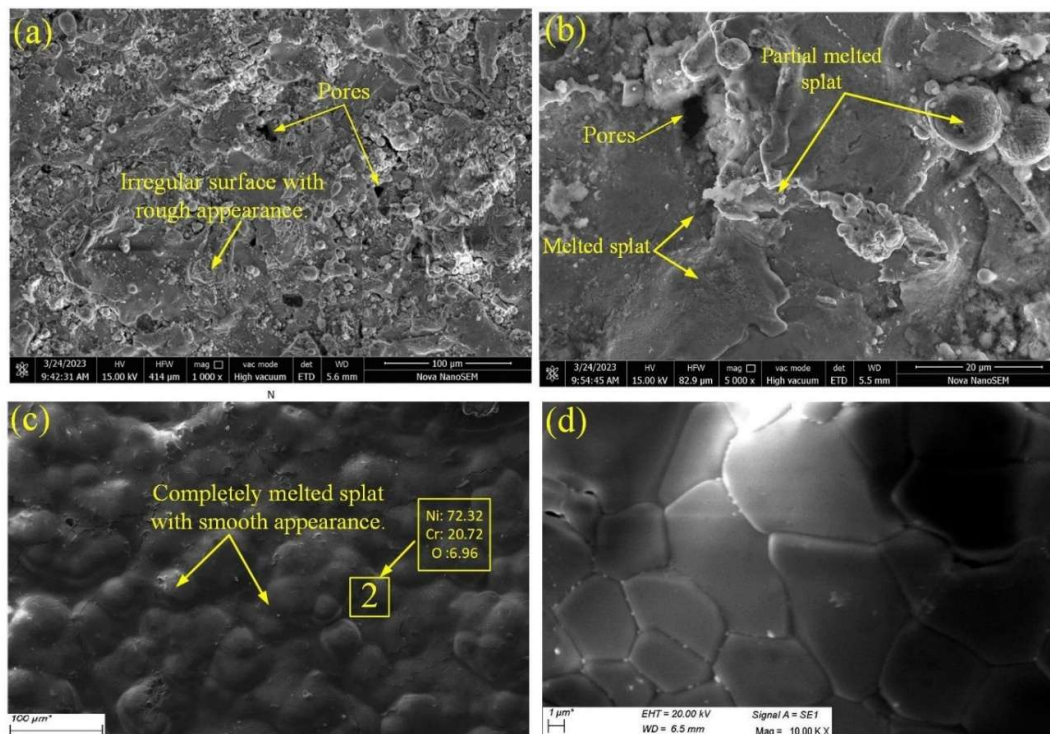


Figure 2. (a,b)The scanning electron microscopy (SEM) image of the cross-section and (c,d,) surface of(Ni-Cr +WC, Co, Cr, cladding.

The microstructure consisted of a relatively uniform Ni-Cr matrix reinforced with dispersed WC-Co-Cr particles. Grain growth was observed due to the volumetric heating generated during microwave processing. Unlike conventional heating, microwave irradiation produced uniform internal heating, resulting in complete melting of the matrix material and improved consolidation of reinforcement particles.

The clad layer exhibited significantly reduced porosity. Most microvoids present in the powder compact disappeared after microwave exposure because molten Ni-Cr flowed into the interparticle spaces, producing a dense coating. The elimination of pores contributes directly to improved hardness and wear resistance by reducing stress concentration sites that can initiate crack propagation.

The interface between the coating and substrate appeared continuous without visible defects, suggesting effective diffusion between the deposited material and stainless-steel substrate as shown in Figure 2. Strong metallurgical bonding is essential because it prevents coating detachment during sliding wear and mechanical loading. The observed bonding quality confirms the suitability of microwave hybrid heating for producing high-integrity surface coatings.

4.3 Elemental Distribution by EDS Mapping

Energy Dispersive Spectroscopy (EDS) analysis confirmed the successful incorporation of the reinforcement particles within the Ni-Cr matrix. Strong peaks corresponding to Ni, Cr, W, Co, Fe, and C were observed in the spectrum.

Nickel constituted the primary matrix element, while chromium contributed to oxidation and corrosion resistance. Tungsten and cobalt originated from WC-Co-Cr reinforcement particles and were distributed throughout the coating. Iron detected during EDS analysis resulted from limited dilution of the SS-304 substrate during microwave cladding.

Elemental mapping demonstrated homogeneous distribution of Ni and Cr across the coating thickness, indicating complete melting and proper alloying during microwave processing. Similarly, tungsten and cobalt were uniformly dispersed, confirming that carbide reinforcement remained well distributed rather than forming large agglomerates.

Only trace quantities of sulphur and magnesium were detected, suggesting minimal contamination during processing. The uniform elemental distribution is expected to contribute to improved hardness and consistent tribological behaviour throughout the coating thickness.

4.4 Phase Analysis Using X-ray Diffraction

X-ray diffraction (XRD) analysis was carried out to identify the phases formed after microwave cladding. The diffraction patterns confirmed the presence of nickel-rich solid solution together with chromium-containing phases and tungsten carbide.

The formation of hard carbide phases plays an important role in improving wear resistance. These carbides act as load-bearing constituents during sliding contact and reduce plastic deformation of the coating surface. Furthermore, chromium contributes to the formation of stable protective oxide layers during service, thereby enhancing oxidation resistance.

No evidence of undesirable brittle phases or severe decomposition of tungsten carbide was observed, indicating that microwave hybrid heating provides controlled thermal exposure capable of preserving reinforcement integrity. The XRD results therefore support the SEM observations showing successful development of a dense composite microstructure.

4.5 Microhardness Analysis

Microhardness evaluation demonstrated a substantial improvement in surface hardness after microwave cladding. The average hardness of the SS-304 substrate was measured as approximately 230 ± 10 HV, whereas the microwave-developed Ni-Cr/WC-Co-Cr composite cladding exhibited an average hardness of 660 ± 12 HV. This represents an increase of nearly 2.9 times compared with the substrate. The remarkable increase in hardness can be attributed to several interacting mechanisms. First, the presence of extremely hard WC-Co-Cr reinforcement particles significantly increases resistance to localized plastic deformation. Secondly, microwave hybrid heating produces uniform melting and solidification, resulting in a dense microstructure with minimal porosity. Reduced porosity improves load transfer within the coating and minimizes crack initiation sites.

Another important factor responsible for hardness improvement is strong metallurgical bonding between splats formed during microwave processing. Complete melting enables adjacent particles to fuse effectively, producing continuous grain boundaries with improved cohesion. The increase in hardness directly influences tribological behaviour because harder materials resist abrasive penetration more effectively during sliding contact. Consequently, the developed composite cladding is expected to exhibit superior wear resistance compared with uncoated stainless steel.

4.6 Sliding Wear Behaviour

The tribological performance of the developed coating was evaluated using a pin-on-disc tribometer under ASTM G99 conditions. The cumulative weight-loss measurements clearly demonstrated superior wear resistance of the microwave-cladded specimens. The uncoated SS-304 substrate exhibited rapid material removal throughout the sliding test due to its relatively low hardness. In contrast, the composite clad showed significantly lower weight loss under identical testing conditions. The substrate experienced approximately 0.0680 g cumulative weight loss during sliding, whereas the microwave-developed composite coating exhibited only 0.0018 g weight loss. This substantial reduction demonstrates the effectiveness of WC-Co-Cr reinforcement in improving wear resistance. The coating exhibited nearly four times greater wear resistance than the substrate. The wear coefficient calculated using Archard's wear equation also showed considerably lower values for the composite cladding. Lower wear coefficient indicates improved resistance to material removal during sliding contact.

The improved tribological behaviour results from several factors including:

- Increased hardness of the composite coating.
- Uniform distribution of hard carbide particles.
- Strong metallurgical bonding.
- Reduced porosity.
- Dense microstructure produced through microwave hybrid heating.

The combination of these characteristics enables the coating to withstand repeated sliding contact without severe material removal.

4.7 SEM Analysis of Worn Surfaces

SEM examination of the worn substrate revealed extensive plastic deformation accompanied by deep grooves, severe scratching, ploughing marks, and abrasive wear tracks as shown in Figure.3..

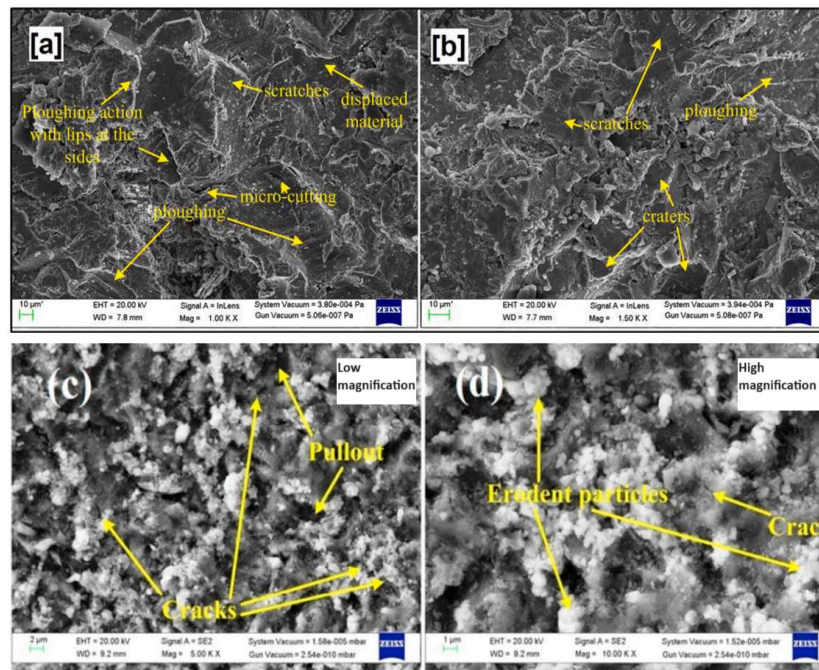


Figure 3. The scanning electron microscopy (SEM) of the substrate at 1000x and 2500x magnification (a and b), as well as SEM images of worn-out microwave treated cladding at 150x and 1000x magnification (c and d).

These features indicate that abrasion was the dominant wear mechanism operating in the uncoated stainless steel. During sliding, hard asperities from the counterface penetrated the relatively soft substrate surface, producing deep furrows and continuous material removal. Large regions of plastically deformed material were observed, indicating insufficient hardness to resist repeated loading. In contrast, the microwave-developed composite coating exhibited significantly different wear morphology. Only shallow abrasion marks and limited micro-cutting were visible on the worn surface.

Localized pitting occurred at isolated locations where reinforcement particles were dislodged during prolonged sliding. However, severe plastic deformation was absent because the hard carbide particles effectively resisted penetration by the counterface. Minor ploughing marks were observed, but their depth remained considerably smaller than those found on the substrate. These observations confirm that the carbide reinforcement effectively protected the Ni-Cr matrix from extensive material removal. The reduced severity of wear scars demonstrates that microwave cladding successfully enhanced the tribological behaviour of SS-304.

4.8 Relationship Between Microstructure and Tribological Performance

The experimental results clearly establish a strong relationship between coating microstructure and wear behaviour. Microwave hybrid heating produced volumetric heating, allowing complete melting of the Ni-Cr matrix while preserving the uniformly dispersed WC-Co-Cr reinforcement. The resulting dense microstructure minimized internal defects such as pores and microcracks. Reduced porosity enhanced load-bearing capability during sliding contact, while strong metallurgical bonding prevented coating delamination.

Simultaneously, uniformly distributed carbide particles acted as barriers against abrasive penetration, thereby decreasing plastic deformation. These combined mechanisms produced the observed improvement in hardness and wear resistance. The superior tribological performance of the developed composite coating therefore originates from the synergistic interaction between microwave processing, dense microstructure, carbide reinforcement, and metallurgical bonding.

4.9 Overall Discussion

The results obtained in this investigation demonstrate that microwave hybrid heating is an effective surface engineering technique for developing wear-resistant composite coatings on stainless steel. Compared with the uncoated SS-304 substrate, the developed Ni-Cr/WC-Co-Cr cladding exhibited:

- * Dense and homogeneous microstructure.
- * Excellent metallurgical bonding.
- * Uniform elemental distribution.
- * Presence of hard carbide phases.
- * Nearly threefold increase in microhardness.
- * Approximately fourfold improvement in wear resistance.
- * Significant reduction in abrasion and plastic deformation.

The combination of SEM, EDS, XRD, hardness testing, and tribological evaluation consistently indicates that incorporation of WC-Co-Cr reinforcement into the Ni-Cr matrix substantially enhances coating performance. The results further confirm that microwave hybrid heating provides rapid volumetric heating with minimal thermal damage, making it a promising alternative to conventional cladding technologies. The developed composite coating is therefore suitable for engineering applications involving severe sliding wear, elevated temperatures, and demanding service conditions where long component life and high reliability are required.

5. Conclusion

The present study successfully developed Ni-Cr reinforced WC-Co-Cr composite cladding on SS-304 using microwave hybrid heating and demonstrated significant improvements in microstructure, hardness, and tribological performance. The major conclusions are summarized below:

1. Microwave hybrid heating successfully produced dense Ni-Cr/WC-Co-Cr cladding with excellent metallurgical bonding on SS-304 within 15 minutes.
2. SEM and EDS confirmed uniform reinforcement distribution, dense microstructure, and negligible porosity throughout the developed composite cladding.
3. XRD analysis confirmed the formation and retention of hard carbide phases responsible for improved mechanical and tribological properties.
4. Composite cladding achieved 660 ± 12 HV, approximately 2.9 times higher hardness than the 230 ± 10 HV SS-304 substrate.
5. Wear weight loss decreased from 0.0680 g to 0.0018 g, indicating approximately 97% improvement in wear resistance.
6. The composite coating exhibited a significantly lower abrasive wear coefficient than the uncoated SS-304 substrate under identical conditions.
7. SEM of worn surfaces revealed shallow grooves and limited abrasion, replacing severe ploughing and plastic deformation observed in SS-304.
8. Microwave-deposited Ni-Cr/WC-Co-Cr cladding significantly enhanced hardness and tribological performance, making it suitable for severe wear applications.

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