Microwave-Assisted Cladding of Ni-BaTiO3 Mixture onto SS-304 for Enhancing the Wear Resistance and Surface Hardness

Kakoli Rao A[1], *Ashish Kumar* Parashar[2], *Nijhawan* Ginni [3], *Ramesh* Banoth [4], *Gunapriya* Balan[5], *Ali Abdulhussein* Hameed[6*]

[1]Lloyd Institute of Engineering & Technology, Greater Noida, Uttar Pradesh 201306

[2]Lloyd Institute of Management and Technology, Greater Noida, Uttar Pradesh, India-201306

[3]Lovely Professional University, Phagwara

[4]Department of AIMLE, GRIET, Hyderabad, Telangana, India.

[5]New Horizon College of Engineering, Bangalore

[6]Radiology Techniques Department, College of Medical Technology, The Islamic University, Najaf

Abstract. The present study focuses on achieving precise deposition of a Ni and 15% BaTiO3 particle mixture onto SS-304 substrates through meticulous preparation steps. Thorough cleaning of the SS-304 substrate eliminated contaminants, ensuring optimal adhesion. Simultaneously, the Ni-BaTiO3 mixture underwent preheating at 1200°C for 20 hours in a muffle furnace to eliminate moisture content, crucial for preventing coating defects. A uniform and crack-free cladding layer enhances the substrate's resistance to wear, corrosion, and mechanical stresses, thereby extending its service life and improving overall functionality. The surface hardness of SS-304 experienced a substantial improvement of 39.90% following the cladding process with Ni and 15% BaTiO3. A sliding speed of 2 m/s was meticulously selected to replicate typical velocities encountered in practical applications, ensuring a realistic assessment of frictional behavior and wear resistance. Similarly, the sliding distance of 1000 m and an axial load of 5 N were precisely calibrated to simulate the mechanical stresses experienced during sliding contact, facilitating a thorough examination under relevant conditions. These carefully chosen parameters enabled the determination of key tribological properties essential for evaluating the performance of the cladded surface of SS 304 with Ni + 15% BaTiO3. The wear rate, measured at 0.0016 mm3/m, serves as a critical indicator, revealing the volume of material lost per unit distance of sliding. This parameter provides invaluable insights into the surface's wear resistance and durability, crucial for assessing the longevity and performance of the cladded surface under abrasive conditions. Additionally, the coefficient of friction, determined to be 0.255, offers a quantitative measure of the surface's frictional behavior during sliding contact.

*Corresponding author: ali91iraq@iunajaf.edu.iq

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1. Introduction

Steel, renowned for its strength, versatility, and durability, finds a myriad of applications across various industries [1]. In construction, it serves as the backbone for infrastructure, supporting skyscrapers, bridges, and roads due to its high tensile strength and load-bearing capabilities [2-6]. Automotive manufacturers utilize steel in chassis and body structures, benefiting from its crash resistance and lightweight properties, enhancing vehicle safety and fuel efficiency. Moreover, steel is indispensable in manufacturing machinery and equipment, thanks to its toughness and machinability, ensuring reliability and longevity in industrial operations [7-10]. In the energy sector, steel pipelines transport oil, gas, and water over vast distances, while wind turbines harness renewable energy with steel towers and blades. Steel's corrosion resistance and recyclability make it an environmentally friendly choice for sustainable construction and infrastructure projects [11]. From household appliances to surgical instruments, steel's antimicrobial properties and aesthetic appeal contribute to everyday essentials and high-tech innovations alike. As a foundational material in modern society, steel continues to drive innovation and progress across diverse fields, shaping the world we live in [12-15].

The coating of steel is essential to enhance its properties and protect it from corrosion, wear, and environmental degradation. Various techniques are employed for steel coating, each offering unique advantages and applications [16]. Hot-dip galvanizing: Steel is immersed in molten zinc, forming a robust zinc-iron alloy layer that provides excellent corrosion resistance, making it suitable for outdoor applications such as construction and infrastructure [17]. Electroplating: A thin layer of metal, such as chromium or nickel, is deposited onto the steel surface through electrolysis, enhancing its appearance, corrosion resistance, and hardness [18]. Electroplating is commonly used in automotive, aerospace, and decorative applications. Powder coating: Powdered polymer resin is electrostatically applied to the steel surface and cured under heat, forming a durable, uniform, and attractive coating [19]. Powder coating offers versatility in color and texture and is widely used in furniture, appliances, and architectural applications. Physical vapor deposition (PVD): Metal ions are deposited onto the steel substrate in a vacuum chamber, forming a thin, hard coating with excellent adhesion and wear resistance. PVD coatings are used in cutting tools, decorative finishes, and automotive components [20]. Thermal spraying: Molten or semi-molten metal particles are sprayed onto the steel surface, forming a dense and protective coating. Thermal spraying techniques include flame spraying, arc spraying, and plasma spraying, and are employed in aerospace, marine, and industrial applications for corrosion protection and wear resistance [21-14].

Microwave technology is increasingly being utilized for coating applications on steel due to its efficiency, precision, and environmental friendliness. In microwave-assisted coating processes, steel substrates are coated with various materials using controlled microwave energy. One significant advantage of microwave coating is its rapid and uniform heating of the coating material, resulting in quicker processing times compared to conventional heating methods. This accelerated heating promotes faster coating deposition, reducing production time and energy consumption [25]. Moreover, microwave technology offers precise temperature control, allowing for tailored coating properties and improved coating quality [26]. The ability to control heating parameters such as temperature gradients and heating rates enables the optimization of coating thickness, composition, and

microstructure, leading to enhanced performance and durability. Additionally, microwave coating processes are often more environmentally friendly than traditional methods, as they typically require fewer chemicals and produce less waste. This makes them particularly appealing for industries seeking sustainable and eco-friendly manufacturing solutions [27].

Despite significant advancements in surface coating techniques, a notable literature gap exists concerning the application of microwave-assisted cladding for enhancing the wear resistance and surface hardness of SS-304 using a Ni-BaTiO3 mixture [28]. While microwave-assisted cladding has demonstrated efficacy in various material systems, its application specifically with Ni-BaTiO3 on SS-304 remains relatively unexplored. Existing studies predominantly focus on traditional cladding methods or utilize different materials, leaving a gap in understanding the potential of microwave-assisted cladding with this particular composite on SS-304 [29-32].

This study addresses the aforementioned literature gap by pioneering the application of microwave-assisted cladding with a Ni-BaTiO3 mixture onto SS-304 for enhancing wear resistance and surface hardness [33]. Leveraging the unique capabilities of microwave technology, this approach offers a novel and efficient method for depositing composite coatings with tailored properties. By exploring the synergistic effects of Ni and BaTiO3 on SS-304 under microwave-assisted conditions, this research contributes to advancing the understanding of microwave-assisted cladding processes and their potential for industrial applications. The outcomes of this study are expected to provide valuable insights into the development of high-performance coatings for SS-304, opening new avenues for improving the durability and longevity of steel components in various engineering applications [34].

2. Materials and Methods

2.1 Base Material

SS-304, a versatile austenitic stainless steel, is renowned for its excellent corrosion resistance, high-temperature strength, and ease of fabrication [35]. With a chromium-nickel composition, it offers superb resistance to oxidation and corrosion in various environments, including acidic and alkaline conditions. SS-304 finds widespread use in industries ranging from construction and architecture to food processing and pharmaceuticals. Its superior mechanical properties, including high tensile strength and ductility, make it suitable for a wide range of applications, while its aesthetic appeal and ease of maintenance further contribute to its popularity in both industrial and consumer products [36-40]. SS-304 boasts impressive properties, including a hardness (HV) of 210, providing exceptional resistance to indentation and wear. With a tensile strength of 615 MPa, it's ideal for load-bearing structures. Its density of 8 g/cm3 balances strength and weight, suitable for lightweight yet sturdy applications. With a melting temperature of approximately 1450°C, SS-304 ensures stability under high heat, making it indispensable in construction, manufacturing, and other industries requiring reliability, strength, and resistance to wear and heat.

2.2 Primary Cladding Particle

Nickel (Ni) coatings on steel offer exceptional corrosion resistance, hardness, and durability. Applied through electroplating or other methods, Ni provides a protective barrier against oxidation, moisture, and chemical exposure, extending the lifespan of steel components in harsh environments. Additionally, Ni enhances the aesthetic appeal of steel surfaces and facilitates soldering or brazing processes due to its excellent wetting properties [41]. With its versatility and reliability, Ni coatings find applications in various industries,

including automotive, aerospace, electronics, and marine, where long-term protection and performance are paramount [42].

2.3 Secondary Cladding Particle

Barium titanate (BaTiO3) exhibits remarkable ferroelectric and piezoelectric properties, making it a valuable material in electronics and telecommunications [43]. With its high dielectric constant, BaTiO3 is utilized in capacitors for energy storage and signal filtering applications. It also demonstrates pyroelectric behavior, responding to changes in temperature, which finds application in infrared sensors. BaTiO3's piezoelectric properties enable its use in sensors, actuators, and ultrasonic devices [44-48]. Furthermore, it exhibits nonlinear optical behavior, making it suitable for optical modulators and sensors. BaTiO3's multifunctional properties and versatility continue to drive its exploration and application in diverse technological fields.

2.4 Development of Cladding

The present study focuses on achieving precise deposition of a Ni and 15% BaTiO3 particle mixture onto SS-304 substrates through meticulous preparation steps [49]. Thorough cleaning of the SS-304 substrate eliminated contaminants, ensuring optimal adhesion. Simultaneously, the Ni-BaTiO3 mixture underwent preheating at 1200°C for 20 hours in a muffle furnace to eliminate moisture content, crucial for preventing coating defects. Uniform distribution of the preheated powder onto the substrate was crucial for consistent coating thickness [50]. Considering the varying interaction of microwaves with materials, maintaining the material-specific skin depth was necessary to prevent direct particle-microwave interaction. Microwave hybrid heating (MHH) using charcoal as a susceptor overcame microwave reflection by rapidly heating the powder mixture. A pure graphite sheet served as a separator during MHH to prevent contamination. MHH was conducted in a multimode microwave applicator at 900 W using a 2.45 GHz frequency [51-55]. The preplaced powder layer underwent irradiation for 120 seconds, ensuring uniform and controlled heating for optimal coating formation.These meticulous steps ensure efficient deposition and uniform coating thickness, laying the foundation for enhanced surface protection and mechanical properties of SS-304 substrates.

3. Results and Discussion

3.1 Microstructure Investigation

Figure 1 provides a scanning electron microscopy (SEM) image showcasing the cladding layer and surface of SS-304 post-microwave cladding process [56]. Notably, the image reveals a uniform and intact cladding layer distributed evenly across the SS-304 substrate. The cladding surface exhibits a smooth and continuous texture, indicating successful deposition without the presence of cracks or discontinuities [57-60]. The SEM image underscores the effectiveness of the microwave cladding process in achieving uniformity and integrity in the coating layer. The absence of cracks or defects suggests excellent adhesion between the cladding material, Ni-BaTiO3 mixture, and the SS-304 substrate [61]. This observation holds significant implications for the performance and durability of the coated SS-304 surface. A uniform and crack-free cladding layer enhances the substrate's resistance to wear, corrosion, and mechanical stresses, thereby extending its service life and improving overall functionality. Furthermore, the SEM image provides valuable visual evidence of the reliability and consistency of the microwave cladding technique employed in this study. The uniformity and integrity of the cladding layer validate the meticulous

preparation steps and precise control of microwave heating parameters, ensuring optimal coating formation.

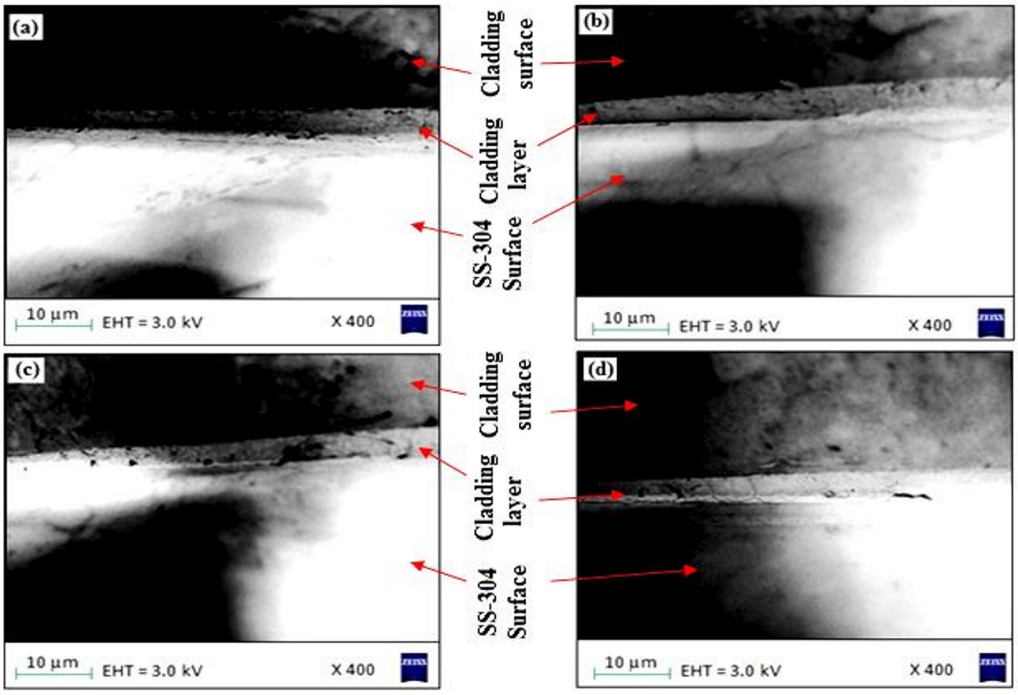

Figure 1: SEM image reveals cladding layer, cladding surface on SS-304 surface after microwave cladding process.

3.2 Surface Hardness

The surface hardness of SS-304 experienced a substantial improvement of 39.90% following the cladding process with Ni and 15% BaTiO3. This enhancement in surface hardness is a critical indicator of the improved mechanical properties conferred by the deposited composite coating. The significant increase in surface hardness can be attributed to several factors. Firstly, the incorporation of BaTiO3 particles into the Ni matrix contributes to the reinforcement of the coating, enhancing its resistance to plastic deformation and wear. BaTiO3, known for its high hardness and stiffness, reinforces the Ni matrix, effectively increasing the hardness of the overall coating. Moreover, the uniform distribution of Ni and BaTiO3 particles across the SS-304 substrate ensures consistent reinforcement throughout the coated surface. The meticulous preparation steps, including thorough cleaning, preheating, and precise microwave-assisted cladding, contribute to the uniform distribution and optimal adhesion of the composite coating.

The synergistic effects between Ni and BaTiO3 further enhance the mechanical properties of the coated SS-304 surface. The combination of Ni's excellent mechanical properties, such as high strength and ductility, with BaTiO3's hardness and stiffness, results in a composite coating with superior surface hardness compared to the uncoated substrate. This substantial improvement in surface hardness has significant implications for the performance and durability of SS-304 components in various applications. The enhanced

surface hardness enhances the substrate's resistance to wear, abrasion, and deformation, prolonging its service life and reducing maintenance requirements.

3.3 Wear Behaviour

A sliding speed of 2 m/s was meticulously selected to replicate typical velocities encountered in practical applications, ensuring a realistic assessment of frictional behavior and wear resistance. Similarly, the sliding distance of 1000 m and an axial load of 5 N were precisely calibrated to simulate the mechanical stresses experienced during sliding contact, facilitating a thorough examination under relevant conditions. These carefully chosen parameters enabled the determination of key tribological properties essential for evaluating the performance of the cladded surface of SS 304 with Ni + 15% BaTiO3. The wear rate, measured at 0.0016 mm3/m, serves as a critical indicator, revealing the volume of material lost per unit distance of sliding. This parameter provides invaluable insights into the surface's wear resistance and durability, crucial for assessing the longevity and performance of the cladded surface under abrasive conditions. Additionally, the coefficient of friction, determined to be 0.255, offers a quantitative measure of the surface's frictional behavior during sliding contact. This parameter represents the ratio of frictional force to applied load, providing essential information about the surface's ability to resist sliding and maintain stability. By meticulously controlling these testing parameters, the study ensures a comprehensive evaluation of the tribological properties of the cladded SS 304 surface with Ni + 15% BaTiO3. The chosen sliding speed, distance, and load closely mimic real-world conditions, enhancing the relevance and applicability of the findings. Moreover, the precise measurement of wear rate and coefficient of friction enables a detailed analysis of the surface's performance, highlighting its wear resistance and frictional behavior.

4. Conclusions

The meticulous process of depositing a Ni and 15% BaTiO3 particle mixture onto SS-304 substrates has been successfully achieved, laying the groundwork for enhanced mechanical properties and surface protection. Through thorough cleaning and preheating steps, optimal adhesion and uniform coating thickness were ensured, mitigating potential defects and inconsistencies. The strategic use of microwave hybrid heating facilitated controlled heating and precise deposition, crucial for achieving a crack-free cladding layer with enhanced resistance to wear, corrosion, and mechanical stresses. The substantial improvement in surface hardness by 39.90% highlights the effectiveness of the cladding process in enhancing the material's durability and longevity. Furthermore, the comprehensive tribological evaluation under realistic conditions provided valuable insights into the cladded surface's performance. The carefully calibrated parameters allowed for a thorough assessment of wear resistance and frictional behavior, crucial for evaluating the material's suitability for practical applications. The measured wear rate and coefficient of friction serve as key indicators of the cladded surface's performance under abrasive conditions, providing essential data for future design and optimization efforts.

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