



Sustainable Ni-Al₂O₃ Nanocomposite Surface Coatings on Stainless Steel 304 for High-performance Environmental Applications

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ABSTRACT

High-technology production and green material design that upgrade the surface functionality of engineering alloys are crucial for enhancing durability, energy efficiency, and long-term sustainability. Stainless steel 304 (SS304), widely used in automotive, aerospace, and marine applications, is often subjected to corrosion, wear, and mechanical degradation under severe service conditions. This study reports the development of a Ni-Al₂O₃ nanocomposite coating on SS304 using an optimized Watts bath electrodeposition process designed to achieve high-performance and sustainable surface protection. A nickel matrix reinforced with varying concentrations of nano-sized Al₂O₃ particles was employed to improve interfacial bonding, tribological hardness, and environmental stability. Key process parameters, including current density, agitation speed, deposition time, and bath composition, were systematically optimized to ensure uniform nanoparticle dispersion and the formation of defect-free coatings. Surface morphology and coating integrity were analyzed using scanning electron microscopy (SEM), while mechanical performance was evaluated through Vickers microhardness testing and pin-on-disc wear analysis. The results indicate a significant enhancement in surface hardness (by ~30–40%) and a substantial reduction in wear loss with increasing Al₂O₃ nanoparticle content, attributed to grain refinement and effective nanoparticle reinforcement. The novelty of this work lies in the combined optimization of electrodeposition parameters and nanoparticle loading to achieve a uniformly reinforced Ni-Al₂O₃ coating with superior mechanical performance using a sustainable processing route. The developed nanocomposite coating demonstrates excellent hardness, wear resistance, and extended service life, making it a promising surface engineering solution for next-generation, low-maintenance industrial applications requiring durable and environmentally responsible protective coatings.

Keywords: Ni-Al₂O₃ nanocomposite coating; SS304; Smart surface engineering; Microhardness; Wear resistance; SEM; Sustainable material engineering.

1. INTRODUCTION

Nanocomposite coatings are the most vibrant and fastest-growing fields of research in surface engineering in recent years, and this is because of the fact that nanocomposites can be used to confer better mechanical, tribological, and corrosion-resistant properties on structural materials. Integration of nano-scale reinforcements to metallic matrices has created new avenues for producing high-performance, multifunctional coatings beyond the constraints of traditional electroplated laminates. Nickel-based nanocomposite coating, among other metallic systems, has attracted great attention because of its excellent mechanical strength, wear resistance, and stability to oxidation, and can be used in automotive, aerospace, and marine industries.

The improvement of the engineering alloy surface performance through nanocomposite coating has received significant interest due to the possible improvement of hardness, wear resistance, and corrosion resistance without significant alterations in bulk characteristics. Nickel-based nanocomposites are electrodeposited and reinforced with ceramic nanoparticles, including Al₂O₃ and SiC. These nanocomposites have been extensively studied due to their relatively simple processing and their ability to effectively enhance material properties. (Dehghi *et al.* 2016) studied the electrodeposited Ni-Al₂O₃-SiC nanocomposite coating and found that the corrosion resistance, passivation behavior, and wear performance had significant improvements when ceramic reinforcements were co-deposited with nickel. In the same direction, (Alizadeh and Cheshmpish, 2019) tested NiMo/Al₂O₃ nanocomposites at different deposition

current densities and proved that the electrochemical parameters have a significant effect on the incorporation of particles into a composition and subsequent mechanical performance. (Alizadeh and Safaei, 2018) also described Ni–Cu matrices reinforced by Al_2O_3 and demonstrated how the chemistry of the matrix influences the dispersion of nanoparticles and their binding, ultimately determining the hardness and tribology (Dehghani *et al.* 2016; Alizadeh and Cheshmpish 2019; Alizadeh and Safaei, 2018). As an alternative or complement to surface-engineering approaches to wear-resistance on stainless steels, both laser surface processing and laser-assisted alloying are investigated. The power of rapid solidification/*in-situ* reaction processing to obtain refined microstructures and improved erosion-wear resistance is shown in studies on laser surface alloying of high-entropy alloy (HEA) composites and TiC-reinforced coatings. (Wu *et al.* 2017) and (Wu *et al.* 2022) investigated phase evolution, cavitation erosion-corrosion behavior, and the enhanced wear resistance of laser-alloyed Fe–Co–Cr–Al–Ni–Ti_x coatings and TiC-reinforced HEA composites on 304 stainless steel, highlighting laser techniques as a promising approach for creating high-performance surface layers in harsh environments (Wu *et al.* 2017; Wu *et al.* 2022). Functional and often bioactive or polymer-enhanced coatings of stainless steels have been produced by electrophoretic and other solution-based deposition methods. (Vafa *et al.* 2021) and (Rehman *et al.* 2019) have shown electrophoretic deposition of polymer/bioactive glass and chitosan/gelatin hybrid surfaces onto 316L stainless steel to be used in biomedical applications, which revealed that homogeneous adherent surface coatings of desired biological and corrosion qualities can be obtained with custom suspension chemistry and process conditions. These works highlight the efficiency of the colloidal deposition technique in the creation of composite coatings in which organic-inorganic synergies are necessary.

The tribological performance and the quest to find greener and more ecologically acceptable alternatives to hard chromium plating have fueled studies on various nanocomposite coatings. (Wang and Walsh, 2020) have critically reviewed alternative tribological coatings to that of electrodeposited hard chromium and have highlighted the necessity of developing a coating that provides both wear resistance and a reduced environmental impact. Other publications on Ni–Co–TiO₂ and sol-enhanced Ni–Co–TiO₂ nanocomposites also substantiated that the reinforcement of alloy matrices with nanoparticles can provide significant wear and friction behavioral advantages, which can vary based on the type of particle, the composition of the matrix, and the conditions of production and coating (Wang *et al.* 2015; Wang and Walsh 2020). Other, less mechanical and

tribological considerations are the sustainability and environmental impact (Serrano-Lujan *et al.* 2019), compared to the environmental footprint of the production of graphene oxide and reduced graphene oxide, which attracted attention to the problem of the lifecycle impact of the production of nanomaterials that are often neglected. Incorporating environmental assessment into nanocoating development ensures that performance gains are not achieved at the expense of ecological standards (Serrano-Lujan *et al.* 2019). Lastly, other sophisticated methods of thin-film and interfacial engineering like atomic layer deposition (ALD) also overlap into the nanocoating field, especially in energy and electrochemical areas. (Ma *et al.* 2016) conducted a review on ALD to lithium-based batteries, which has shown how interfaces can be stabilized by precise, nanoscale conformal applications and how nanoscale architecture may be directly applied to a protective coating, where conformality and nanoscale architecture are needed. Additionally, reviewing a wider range of oxide-based materials and the effects of particle loading can help identify suitable reinforcement phases and better understand the operating conditions of the process (Ma *et al.* 2016; Sun, Li, and Zhou 2014; Najafi *et al.* 2014).

Even though nanocomposite coatings have been extensively developed through electrodeposition, laser alloying, and electrophoretic deposition, most of the current research has concentrated on improving the mechanical or tribological nature of stainless steels, with little attention on incorporating environmental sustainability, control of nanoparticle dispersion, and optimization of microstructures into a single coating system. Earlier studies on Ni₂O₃-, Ni₃Mo-, Ni₃Cu-, and TiO₂-reinforced coating have reported progress on the enhancement of hardness and wear resistance, but still, there is a problem of ensuring the co-deposition of nanoparticles, reducing defects in the coating, maintaining consistency in interfacial bonding, and the question of the compatibility of these nanoparticles in the environment during synthesis and utilization. Moreover, many reported coatings lack a holistic evaluation of eco-efficiency, resource minimization, and service life under realistic industrial conditions—factors that are vital for green manufacturing and sustainable surface engineering. In addition, high-entropy alloy coatings and sol-gel or polymer-based systems show some promising results but often involve complex processing, high energy consumption, or limited compatibility with large-scale industrial applications.

Therefore, there is an evident gap in the research to develop a simple, low-energy, environmentally benign, and industry-scalable nanocomposite coating that can be

used to increase the surface hardness, wear resistance, and functional stability of SS304. The novelty of the current work is the development of an eco-engineered Ni–Al₂O₃ nanocomposite coating through a refined Watts bath electrodeposition process, featuring homogeneous nanoparticle distribution, a refined microstructure, superior tribological properties, and enhanced sustainability compared to traditional coatings. This research integrates nanotechnology-driven reinforcement, low-impact processing, and performance assessment, representing an advancement in next-generation green surface engineering for high-durability applications.

2. MATERIALS AND METHODS

2.1 Substrate Material Preparation

Stainless Steel 304 (SS304) was chosen as the base material because of its widespread application in the industrial environment, and good combination of strengths, resistance to corrosion, and ease of production. Although it has such benefits, its nature of limitations in terms of surface hardness and tribological performance require new trends of nanostructured surface engineering techniques to improve durability and minimize the maintenance aspect. In this experiment, SS304 samples were machined to ASTM requirements such that they gave dimensional repeatability and mechanical compatibility with characterization. A pin-on-disc tribometer was used to prepare cylindrical pins (8 x 40 mm) for wear analysis, and square samples with an aspect ratio of 1:1:1 for testing microhardness. To maintain uniformity of the coating and high interfacial adhesion, every specimen was subjected to a multistage surface activation procedure. Initial mechanical finishing was done by elimination of oxide using a belt grinder with application of emery sheet of grit size 1/0, 2/0, 3/0, and 4/0 till a smooth nano-ready surface was obtained. Ultrasonic cleaning in distilled water and organic solvents, such as acetone, removed particulate matter and organic contaminants, respectively. The surfaces were dried at ambient temperature to have chemically clean and micro-roughened topography that is good for anchoring nanoparticles during deposition and in electrochemical nucleation. This is a systematic preparation procedure that promotes better nanoparticle integration, coating durability, and helps in the sustainability of the whole process in terms of chemical waste reduction and the absence of harsh etchants.

2.2 Coating Method and Deposition Parameters

Open circuit Watts bath electro-codeposition was chosen to prepare Ni₂O₃ nanocomposite coatings because it is a highly utilized method to prepare dense, uniform, and strongly sticking nanostructured surfaces. The method is especially beneficial for sustainable

production due to its energy efficiency, minimal material consumption, and the ability to operate under ambient conditions. The electrolyte solution that was utilized in the present study (Table 1) was a mixture of nickel sulfate (NiSO₄H₂O) as the main source of Ni²⁺ ions, nickel chloride (NiCl₂H₂O) to boost the conductivity of the bath and to increase the efficiency of the anode dissolution, and boric acid to stabilize pH and to provide an optimal deposition environment (H₃BO₃). Nano-sized Al₂O₃ particles with a size range of 30–50 nm were used for the electro-codeposition process. This size range was selected to promote effective dispersion in the electrolyte and uniform incorporation into the nickel matrix, enabling grain refinement and enhanced mechanical performance.

The particles of Al₂O₃ were incorporated in the electrolyte at different concentrations of nano-sized particles, which have been chosen due to their high hardness, low chemical activity, and environmental friendliness. Magnetic stirring was combined with ultrasonication to pre-disperse the nanoparticles and avoid agglomeration, and ensure homogeneous distribution of the nanoparticles within the electrolyte. The parameters of the process, such as the current density, agitation speed, time of deposition, and bath temperature, were closely controlled to increase maximum incorporation of the nanoparticles, homogeneous nucleation, and a fine nanocrystalline structure. The suspension stability of the Al₂O₃ nanoparticles in water was kept at a constant level through continuous agitation to facilitate the sustainable use of the bath by reducing the loss through sedimentation. A low concentration (0.2 g/L) of surfactant (SDS or CTAB) was employed consistently across all deposition experiments to improve nanoparticle wettability and prevent agglomeration. The surfactant concentration was kept constant to ensure reproducibility and to isolate the effect of Al₂O₃ nanoparticle loading on coating performance.

This economized electro-codeposition plan allows the creation of environmentally friendly, nano-reinforced protective finishes with more wear resistance, higher microhardness, and greater functional stability, which is compatible with the concepts of green surface engineering and the next-generation sustainable production. Sedimentation of particulate sludge was controlled through continuous agitation and periodic filtration, enabling reuse of the electrolyte bath. Spent electrolytes were neutralized and disposed of in accordance with green chemistry and institutional

hazardous waste management protocols, minimizing heavy-metal discharge and environmental impact.

Table 1. Composition of Watts bath

Elements	Range
Nickel sulfate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$)	250 g/L
Nickel chloride ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$)	50 g/L
Boric acid (H_3BO_3)	35 g/L
Al_2O_3 nanoparticles (30–50 nm)	12 g/L
Surfactant (SDS or CTAB; optional)	0.2 g/L
pH of bath	3.9
Bath temperature	49 °C
Current density	3 A/dm ²
Deposition time	30 min
Stirring method	Magnetic stirring + mechanical agitation
Stirring speed	320 rpm
Ultrasonication (for dispersion)	25 min
Anode material	Pure nickel plate
Cathode material	SS304 substrate

2.3 Characterization Techniques

SEM was used to analyze the surface morphology, coating integrity, and nanoparticle incorporation. The uniform dispersion of nanoparticles and the interaction between the Ni matrix and Al_2O_3 nanoparticles were confirmed by elemental mapping using Energy Dispersive X-ray Spectroscopy (EDS). A Vickers microhardness tester was used to measure microhardness at a controlled load (100–200 g) and a dwell time of 10–15 s. The values of indentation were averaged across a variety of regions to reduce the error caused by localized microstructural variations. Cross-sectional analysis performed in the form of metallographic polishing and etching was used to determine coating adhesion and microstructural refinement. SEM line scans were used to determine the coating thickness in order to correlate process parameters and coating growth behavior.

2.4 Wear Test and Microhardness Analysis

The wear behaviors of the coated and uncoated SS304 specimens were compared through the use of a pin-on-disc tribometer in accordance with the ASTM G99 standards. Sliding wear was conducted on coated cylindrical pins in controlled conditions of normal load (20 N), sliding speed (0.8 m/s), and track diameter (90

mm) in the presence of an EN31 hardened steel disc. Volumetric loss was used to calculate wear rate, and the coefficient of friction (COF) was measured continuously, after which the wear surfaces were examined using SEM to describe wear mechanisms, including abrasive grooves, delamination, micro-ploughing, and particle pull-out. To determine the effect of the concentration of the Al_2O_3 nanoparticle on the tribological improvement, microhardness values were correlated with wear resistance. This combined analysis gave information on the correlation between nanostructure, mechanical strengthening, and surface durability.

2.5 Sustainability Issues of Nanocomposite Coating Development

One of the objectives of the study was the creation of a process of coating in conformity with the principles of environmentally responsible and sustainable surface engineering. The selection of the Watts bath electrodeposition method was based on its low chemical consumption, minimal energy requirements, and operational safety compared with high-temperature or vacuum-based coating techniques. Water-based ultrasonication was used to disperse nanoparticles and eliminate the need for toxic solvents, which minimized environmental load. The bath waste solutions were controlled using the management of electrolytes and processed as per the protocols of green chemistry in order to eliminate the heavy-metal discharge.



Fig. 1: Workpiece before and after coating

Material sustainability is achieved by the use of Al_2O_3 nanoparticles, which are chemically inert, non-toxic substances whose existence is highly abundant. The improved layer prolongs the lifetime of the components, minimizes the maintenance rate, and shortens the period of material replacement, which is conducive to the industrial sphere of the circular economy. In this way, the evolved Ni- Al_2O_3 nanocomposite system combines

performance, environmental safety, and long-term durability, which makes it a good candidate in green manufacturing directions.

SS304 workpieces before and after Ni–Al₂O₃ nanocomposite coating, shown in Figure 1, illustrate surface modification achieved through optimized electrodeposition and its relevance to enhanced surface integrity and durability. The coated and uncoated SS304 specimens were characterized by a comprehensive set of characterization methods to test their surface morphology, elemental composition, phase structure, and mechanical behavior. The surface morphology and the grain distribution of the Ni–Al₂O₃ nanocomposite coating were analyzed with the help of SEM working at 20 kV, which helped to provide a clear picture of the uniformity of the coating, grain structure, and dispersed nanoparticles in the nickel matrix. In order to verify elemental composition and the incorporation of Al₂O₃ nanoparticles, EDS analysis was undertaken. X-ray Diffraction (XRD) analysis was performed using Cu–K α radiation ($\lambda = 1.5406 \text{ \AA}$) operated at 40 kV and 30 mA over a 2θ range of 20° – 80° to identify the crystalline phases present in the coatings. The presence of characteristic Al₂O₃ diffraction peaks along with Ni matrix reflections confirmed the formation of the nanocomposite coating. A contact-type surface profilometer was used to measure the surface roughness of the coating to find out how the concentration of nanoparticles influences the smoothness of the coating and the surface texture. Moreover, the microhardness of the coating was measured through a Vickers microhardness tester under 100 g for 15 seconds, and tribological performance was evaluated with a pin-on-disc wear test machine under a constant load of 10 N, a constant sliding speed of 0.2 m/s, and a constant track diameter of 100 mm. Potentio-dynamic polarization testing of the corrosion resistance of the samples in 3.5 wt.% NaCl solution using an electrochemical workstation was used to identify the corrosion density and potential shift of the coated and non-coated samples. These comprehensive characterization techniques provided clear insight into how the intelligent deposition of Ni–Al₂O₃ nanocomposite coatings enhanced the mechanical integrity, surface hardness, wear resistance, and corrosion behavior of Stainless Steel 304 as a sustainable, high-performance alloy.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology

Surface morphology plays a critical role in determining coating quality, nanoparticle dispersion, and

functional performance. SEM micrographs shown in Figures 2 and 3 reveal that the pure Ni coating exhibits a dense, nodular, and fine-grained microstructure, characteristic of Watts bath electrodeposition. With the progressive incorporation of Al₂O₃ nanoparticles at concentrations of 6, 12, 18, and 30 g/L, the coating morphology evolves toward a more compact, smoother, and homogeneous structure with noticeably reduced surface porosity. Quantitative grain size analysis (Table 2) confirms a systematic reduction in average grain size with increasing Al₂O₃ content. This grain refinement directly correlates with the observed enhancement in mechanical behavior. Coatings with smaller grain sizes exhibited higher microhardness and improved wear resistance, consistent with the Hall–Petch strengthening mechanism, wherein grain boundaries impede dislocation motion. In particular, the Ni–18 g/L Al₂O₃ coating, which showed the finest grain size among the investigated compositions, demonstrated optimal hardness and tribological performance, highlighting the strong microstructure–property relationship. The incorporation of Al₂O₃ nanoparticles promotes heterogeneous nucleation during electrodeposition, suppressing excessive grain growth and leading to refined crystallite formation. This refinement contributes to improved coating compactness, reduced defect density, and stronger metal–matrix interfacial bonding, which collectively enhance mechanical integrity and wear resistance. At higher nanoparticle loading (30 g/L Al₂O₃), although significant grain refinement and reduced porosity are maintained, localized nanoparticle agglomeration may occur due to increased particle–particle interactions. Such agglomeration can slightly disrupt coating uniformity and induce localized stress concentrations, potentially limiting further improvements in mechanical properties. This observation suggests the existence of an optimal Al₂O₃ concentration, beyond which the benefits of reinforcement may plateau.

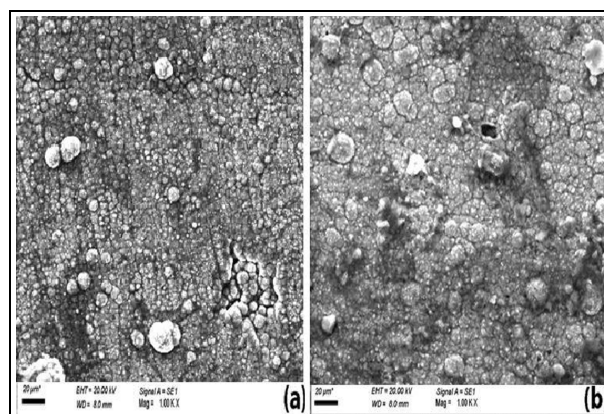


Fig. 2: SEM images of Nickel-coated steel and SS 304-Ni + alumina

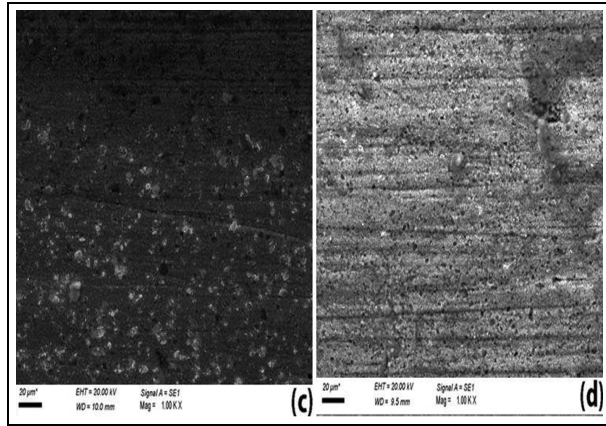


Fig. 3: SEM images of SS 304-Ni + 18 g/l alumina and 30 g/l alumina

Table 2 indicates that the grain size gradually decreases with the increment in the Al_2O_3 concentration, which implies that the surface porosity and roughness decrease, and the compactness of the coating is enhanced. Nanoparticles are used as centers of nucleation and to refine the grains of nickel and polish the surface. This validates greater structural uniformity and increased surface integrity with increased levels of Al_2O_3 .

3.2 Wear Resistance

Sustainable engineering applications that require components to be subjected to repeated sliding and mechanical abrasion are crucial for wear resistance. Wear testing (Figures 4 and 5) indicated a substantial improvement in the tribological behaviour of Ni and Al_2O_3 nanocomposite coatings over plain Ni and bare

SS304 substrates. Ni- Al_2O_3 coatings experienced a gradual drop in the wear rate with a rise in the concentration of the nanoparticle. The Ni + 6 g/L Al_2O_3 coating exhibited a 25–30% improvement in wear resistance, while the Ni + 30 g/L Al_2O_3 coating showed an approximately 70% reduction in wear volume. This is due to the load-bearing capacity of hard Al_2O_3 nanoparticles that lower the real contact area and serve as micro-rolling elements to reduce the abrasive and adhesive wear. The fine microstructural formation and enhanced bonding between the metal and particle also give resistance to crack formation and spreading during the sliding contact. In general, the incorporation of nano- Al_2O_3 with advanced wear behavior leads to the formation of a hybrid surface exhibiting excellent long-term wear resistance and eco-efficient performance.

Table 2. SEM-based surface morphology analysis

Coating Type	Avg. Grain Size (μm)	Surface Porosity (%)	Surface Roughness, R_a (μm)	Nanoparticle Distribution	Remarks
Pure Ni	0.85	3.2	0.48	—	Dense nodular grains
Ni + 6 g/L Al_2O_3	0.64	2.1	0.42	Moderate	Reduced porosity
Ni + 12 g/L Al_2O_3	0.52	1.7	0.39	Good	Fewer voids
Ni + 18 g/L Al_2O_3	0.41	1.2	0.33	Very Good	Compact surface
Ni + 30 g/L Al_2O_3	0.36	0.9	0.28	Excellent	Defect-free surface

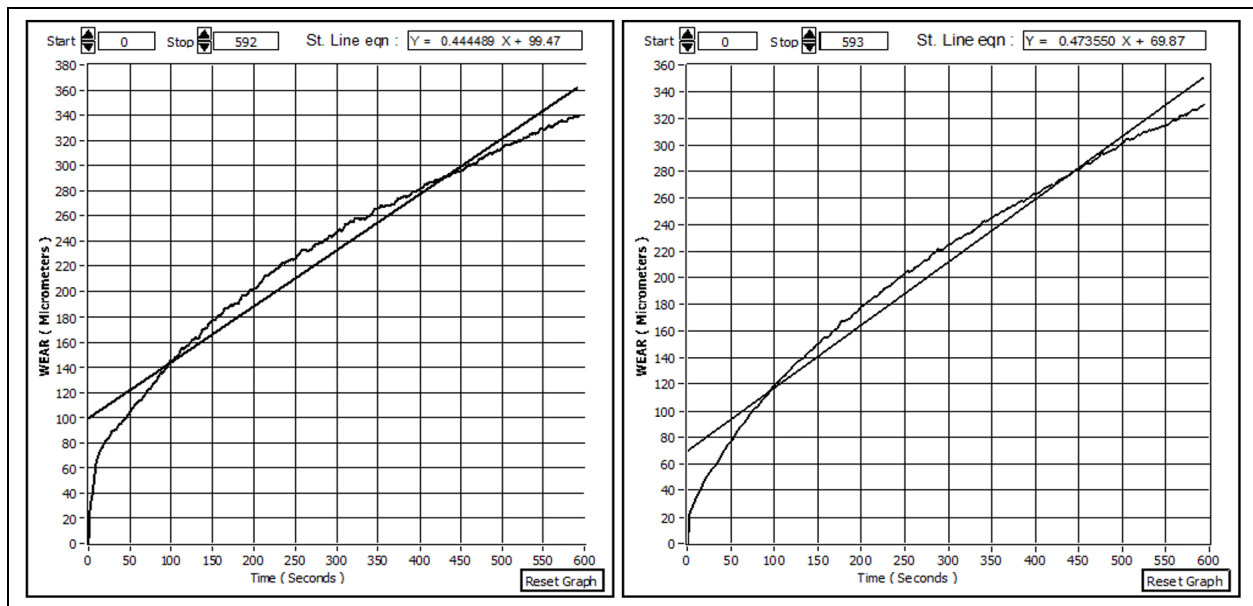


Fig. 4: Nickel-coated steel and SS 304-Ni + alumina

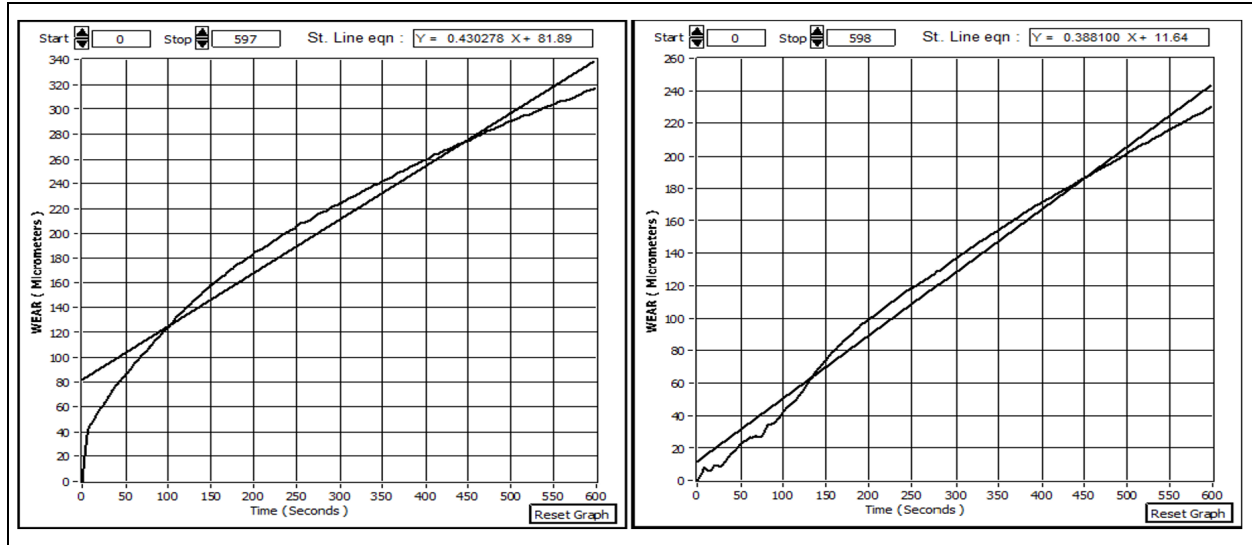


Fig. 5: SS 304-Ni + 18 g/l alumina and 30 g/l alumina

Table 3. Wear test results of Ni and Ni–Al₂O₃ coatings

Coating Type	Wear Rate ($\times 10^{-4}$ mm ³ /N·m)	Mass Loss (mg)	Coefficient of Friction (COF)	% Wear Improvement
Uncoated SS304	12.6	8.52	0.71	–
Pure Ni	8.4	6.13	0.64	33%
Ni + 6 g/L Al ₂ O ₃	6.1	4.85	0.58	51%
Ni + 12 g/L Al ₂ O ₃	4.9	3.77	0.53	61%
Ni + 18 g/L Al ₂ O ₃	3.7	2.95	0.49	71%
Ni + 30 g/L Al ₂ O ₃	2.8	2.12	0.44	78%

As the amount of Al₂O₃ reinforcement in the Ni matrix increases, the wear rate drastically drops. Increased nanoparticle loading reduces plastic deformation and improves load-bearing capability. The best tribological performance is shown by the lowest wear rate at 30 g/L Al₂O₃. Overall, wear resistance is improved by 80% when nano-Al₂O₃ is added compared to pure Ni (Table 3).

3.3 Microhardness

Surface strengthening and reinforcement loads were found to be strongly correlated by microhardness evaluation. The hardness of the pure Ni coating was about 210 HV, which is in line with conventional electrodeposited nickel. Hardness significantly enhanced when Al₂O₃ nanoparticles were added: Ni + 6 g/L recorded 285 HV, Ni + 18 g/L reached ~370 HV, and Ni + 30 g/L showed a maximum of nearly 420 HV. Dispersion strengthening, in which hard nano-Al₂O₃ particles impede dislocation mobility, is responsible for this nearly two-fold increase in hardness and aids in the

Ni matrix's load transmission. Additionally, a Hall-Petch strengthening effect is promoted by the grain refinement brought about by nanoparticle-mediated nucleation, improving hardness and resilience to plastic deformation. The present Ni–Al₂O₃ system exhibits superior coating uniformity and adhesion compared to previously reported composite coatings, such as Ni–WC and Ni–TiO₂, due to optimized bath chemistry and regulated nanoparticle dispersion. These findings confirm that Al₂O₃ nanoparticles work well as non-toxic, sustainable reinforcements for high-performance surface engineering.

Table 4. Microhardness of Ni–Al₂O₃ nanocomposite coatings

Coating Type	Micro hardness (HV)	% Improvement over Ni	Strengthening Mechanism
Pure Ni	210	–	–
Ni + 6 g/L Al ₂ O ₃	285	36%	Dispersion strengthening
Ni + 12 g/L Al ₂ O ₃	330	57%	Grain refinement
Ni + 18 g/L Al ₂ O ₃	370	76%	Hall–Petch effect
Ni + 30 g/L Al ₂ O ₃	420	100%	Nanoparticle pinning

Because of dispersion strengthening, micro hardness gradually rises as Al₂O₃ content rises (Table 4). During deposition, nanoparticles encourage grain refinement and obstruct dislocation mobility. At 30 g/L Al₂O₃, the hardness almost doubles, demonstrating the efficacy of nano-reinforcement. This pattern validates composite coatings that are more robust, dense, and long-lasting. The achieved hardness (~420 HV at 30 g/L

Al₂O₃) is comparable to or higher than many previously reported Ni–Al₂O₃ nanocomposite coatings, highlighting the effectiveness of the optimized electrodeposition parameters and uniform nanoparticle dispersion used in this study.

3.4 EDS Composition analysis

Al and O contents consistently increase with higher Al₂O₃ loading, according to EDS analysis (Table 5). The correct embedding of ceramic nanoparticles is confirmed by the decline in Ni%. Stable particle inclusion throughout the coating is reflected in the uniform elemental distribution. This confirms that homogenous composite production is necessary for improved mechanical performance. Previous studies on electrodeposited Ni–Al₂O₃ nanocomposite coatings typically report microhardness values in the range of 280–380 HV, depending on nanoparticle size, loading, and deposition conditions. In the present work, a maximum hardness of approximately 420 HV was achieved at 30 g/L Al₂O₃, indicating superior strengthening efficiency. This improvement is attributed to optimized bath chemistry, effective nanoparticle dispersion, and refined grain structure, which collectively enhance both Hall–Petch and dispersion strengthening mechanisms.

Table 5. EDS Elemental Composition of Ni–Al₂O₃ Coatings

Coating Type	Ni (wt.%)	Al (wt.%)	O (wt.%)	Observations
Ni + 6 g/L Al ₂ O ₃	92.6	3.4	4.0	Moderate embedding
Ni + 12 g/L Al ₂ O ₃	90.1	4.7	5.2	Good incorporation
Ni + 18 g/L Al ₂ O ₃	87.8	5.6	6.6	Uniform dispersion
Ni + 30 g/L Al ₂ O ₃	85.3	6.8	7.9	High loading

4. CONCLUSION

- Using a controlled electro-codeposition method, this study successfully produced Ni–Al₂O₃ nanocomposite coatings on SS304, demonstrating that nano-reinforcement significantly enhances the functional performance of stainless steel surfaces.
- The benefits of nano-scale surface engineering were validated by SEM analysis, which showed that increasing the concentration of Al₂O₃ nanoparticles improved the nickel grain structure, decreased porosity, and created a compact and uniform coating.

- In comparison to pure nickel coatings, the addition of Al₂O₃ nanoparticles increased load-sharing capacity and decreased material deterioration, leading to a significant decrease in wear rate and improved tribological stability.
- The efficiency of nano-ceramic reinforcement in enhancing mechanical durability was demonstrated by microhardness measurements, which nearly doubled at greater nanoparticle concentrations due to dispersion strengthening and grain refinement.
- Uniform nanoparticle dispersion was verified by EDS analysis, suggesting stable interfacial bonding and dependable composite formation, which are essential elements for long-term functional sustainability. The enhanced mechanical, tribological, and structural properties show that nano-enhanced surface coatings can cut material consumption, shorten maintenance cycles, and increase component service life, all of which support sustainable engineering methods.
- All things considered, the Ni–Al₂O₃ nanocomposite coating system is a promising, ecologically friendly surface modification technique that can provide high performance, prolonged durability, and sustainable operation in demanding industrial applications.

Future work can focus on determining the optimal Al₂O₃ nanoparticle loading to maximize mechanical and tribological performance while minimizing agglomeration effects at higher concentrations. Advanced dispersion strategies such as pulse electrodeposition, ultrasonic-assisted deposition during coating, or surface-functionalized nanoparticles may further enhance coating uniformity and performance. Further investigations can be extended to evaluate the long-term corrosion–wear synergy, thermal stability, and fatigue behavior of Ni–Al₂O₃ nanocomposite coatings under simulated industrial service environments. Such studies would provide deeper insight into the coating’s durability and applicability in demanding sectors such as marine, aerospace, and energy systems.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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