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Enhancing electrochemical performance of nickel nanostructured coatings via ultrasonic-assisted electrodeposition with SiC nanoparticle incorporation

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ABSTRACT

In this study, nickel (Ni) nanostructure coating and Ni/ silicon carbide (SiC) nanocomposite coating were produced by electroplating method under ultrasonically-pulse current on the stainless-steel substrate. The presence of SiC nanoparticles in the Ni matrix caused a change in the preferred orientation from the (200) plane to the (111) plane. The electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization tests were carried out after 1 h in 3.5% NaCl solution. The results of polarization showed that due to the presence of SiC ceramic nanoparticles on the surface of the coating, the corrosion resistance increased by reducing the active metal surface. This was attributed to the neutral nature of the ceramic particles in the corrosive solution. The polarization resistance for the composite coating increased by ~ 61 % compared to pure Ni. Also, the corrosion rate for composite coating compared to pure Ni decreased from 0.0055 to 0.013 mm/year. Vickers microhardness for the composite sample increased by 45 % compared to pure Ni. The Young's modulus for the composite sample increased by 46%.

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1. Introduction

The demand for surface coatings that exhibit exceptional wear resistance, corrosion protection, and high temperature stability has necessitated the development of novel composite materials [1]. The combination of Ni and SiC has shown great potential in addressing these requirements, as it brings together the desirable properties of both materials [2]. Ni provides excellent corrosion resistance, while SiC offers exceptional hardness, thermal stability, and wear resistance [3]. By incorporating SiC nanoparticles into a Ni matrix through the electrodeposition process, it is possible to create composite coatings with enhanced performance characteristics. The microstructural characteristics of Ni/SiC composite coatings significantly impact their mechanical and tribological properties [4]. This section focuses on the analysis techniques employed to study the distribution, size, and morphology of SiC nanoparticles within the Ni matrix. Furthermore, it examines the influence of SiC content, particle size, and deposition parameters on the mechanical properties, such as hardness, adhesion strength, and wear resistance, of the composite coatings. The relationship between the microstructure and the resulting performance properties is elucidated [5,6]. The potential applications of Ni/SiC composite coatings are diverse, ranging from automotive components and cutting tools [7]. This section explores the current and emerging applications of these coatings, highlighting their advantages over conventional coatings. Additionally, it identifies the challenges and opportunities in further improving the properties and expanding the range of applications for Ni/SiC composite coatings [8]. Future research directions, such as optimizing the deposition parameters, developing new synthesis techniques, and exploring novel SiC reinforcement strategies, are also discussed [9]. The electrodeposition technique is commonly used to fabricate Ni/SiC composite coatings due to its versatility and ability to control the composition and microstructure of the coatings [10]. This section briefly describes the electrodeposition process used for the fabrication of Ni/SiC composite coatings, including the key parameters such as current density, bath composition, temperature, and pH [11]. It emphasizes the importance of optimizing the deposition parameters to achieve coatings with desirable corrosion resistance. Corrosion is a pervasive issue that impacts the integrity and lifespan of materials in various industries, including automotive and infrastructure [12]. Surface coatings are widely employed as a protective measure to mitigate corrosion by providing a barrier between the material and

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the corrosive environment [13]. The incorporation of SiC nanoparticles into a Ni matrix via electrodeposition offers a promising approach to enhance the corrosion resistance of coatings [4]. This introduction section provides an overview of the motivation for investigating the corrosion behavior of Ni/SiC composite coatings and highlights the significance of understanding their performance in corrosive environments. In this research, Ni composite coating reinforced with SiC nanoparticles by electrodeposition method was used. The presence of SiC ceramic nanoparticles can increase corrosion resistance by filling small holes and reducing the active metal surface. In this study, the simultaneous effect of ultrasonication and the introduction of SiC nanoparticles has been investigated for the first time.

2. Materials and methods

In this study, nickel powder with a size of less than 45 microns and SiC powder with a diameter of less than 50 nm are used as raw materials. Also, stainless steel was used as a substrate. Then Watts electroplating bath was prepared with $NiSO_4.6H_2O$ (300 g/l), $NiCl_2.7H2O$ (40 g/l), H_3BO_3 (40 g/l) chemical composition.

The steel substrate with dimensions of 3 × 4 cm^2 was washed after polishing and placed in a watt bath as a cathode. Ni sheet with dimensions of 3 × 3 cm^2 was used as anode. A steel substrate with dimensions of 3 × 4 cm² was used as the cathode. Initially, to remove oxides and smooth the surface, the steel substrate was polished to a mirror finish using sandpaper ranging from grit #80 to #3000. Subsequently, a degreasing solution was employed to eliminate any surface contaminants. Finally, before immersion in the electrolyte solution, the substrate was washed with water and soap. Pulse current with a current density of 5 A/dm^2 was used to deposit Ni/SiC composite for 20 minutes. Finally, the composite coating was produced and microstructural characterization and corrosion test. XRD analysis was done by D8 advanced Bruker device, in order to identify the phase and crystal structure. During the plating operation, an ultrasonic bath was used to ensure uniform distribution and no agglomeration. To investigate the electrochemical behavior, solid samples with a 1cm^2 were cut from the coating sample. Next, they were polished and cleaned with deionized water. Electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization tests were performed after immersing the samples in a 3.5% NaCl solution for 2 hours. The corrosion tests were conducted using a with Solarton-SI1287 potentiostat/galvanostat instrument from the United States. electrochemical experiments were conducted at room temperature.

3. Results and discussion

3.1. Phase structure

XRD pattern related to Ni coating and Ni/SiC composite coating, made by electroplating method, was shown in Fig. 1. By adding SiC nanoparticles, the preferred crystallographic texture has changed from the (200) plane to the (111) plane. The grain size was obtained using Scherer's method for both samples. The grain size for the composite sample has decreased from 35 to 22 nm. The reason for this can be attributed to the fact that SiC nanoparticles act as a barrier against grain boundary migration and prevent grain growth [14].

3.2. Mechanical properties

The grain size and Vickers microhardness for pure Ni and Ni/SiC coatings are shown in Fig. 2. The results show that the addition of SiC nanoparticles in the Ni matrix reduces the grain size according to the Zener locking mechanism, in other words, the nanoparticles are placed against the boundaries and act as barriers to delay their growth. On the other hand, this size reduction according to the Hall- Pach mechanism leads to an increase in microhardness. Another mechanism that can affect the mechanical properties and hardness of the composite sample is the dispersion of the hardness of SiC nanoparticles in the matrix, which can act as barriers to the mobility of impurities and lock them, which leads to an increase in the microhardness of the composite sample. In order to confirm the Vickers microhardness results in Fig. 3, the results of the nanoindentation test (force-displacement) were reported. The results of the hardness and Young's modulus are reported in Table 1. It can be seen that the hardness and Young's modulus of the Ni/SiC sample increased due to the addition of SiC nanoparticles.

Table 1
Nano-indentation data of Ni/SiC composite coatings.

Sample	Hardness (GPa)	Young's modulus (GPa)
Ni	3.20	123
Ni/SiC	11.05	180

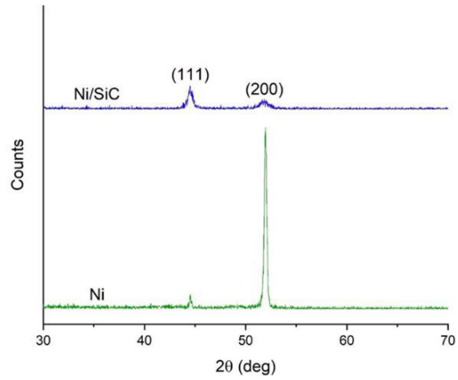

Fig. 1. XRD of Ni and Ni/SiC composite coatings.

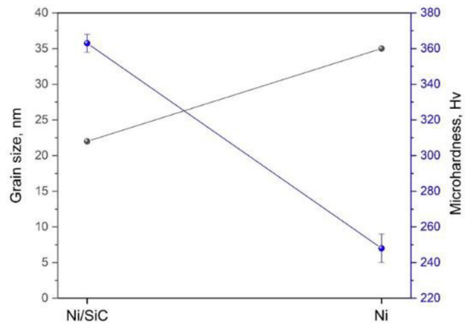

Fig. 2. Micro-hardness and grain size of Ni and Ni/SiC composite coatings.

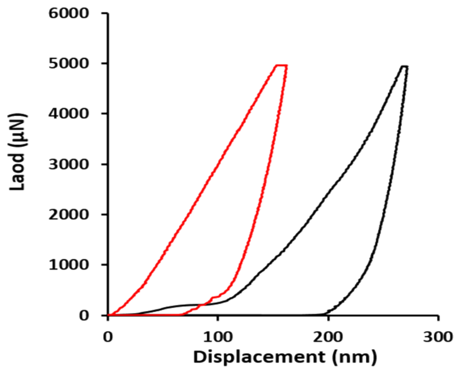

Fig. 3. Nano-indentation of Ni and Ni/SiC composite coatings.

3.3. Electrochemical behaviour

Fig. 4, illustrates the potentiodynamic polarization behavior of Ni coating and Ni/SiC nanocomposite coatings deposited by PC electrodeposition immersed in 3.5 % NaCl solution. Cview software was used to obtain corrosion current density (Icorr), corrosion potential (Ecorr), corrosion rate (rcorr), and polarization resistance (Rp). Polarization parameters are extracted and listed in Table 2. The results show that in the presence of SiC ceramic nanoparticles, the composite sample exhibits a nobler behavior. Also, the current density has decreased for the composite sample. On the other hand, polarization resistance and corrosion rate have increased and decreased, respectively. As a result, the addition of SiC nanoparticles increased the corrosion resistance by reducing the active metal surface and filling [3,15].

Table 2
Potentiodynamic polarization data obtained for the coatings.

Sample	Icorr (A.cm^2)	Ecor r (V)	Rcorr (mm/year)	Rp (Ω.cm^2)
Ni	1.15×10^{-6}	-0.63	0.0134	21376
Ni/SiC	4.73×10^{-7}	-0.52	0.0055	52945

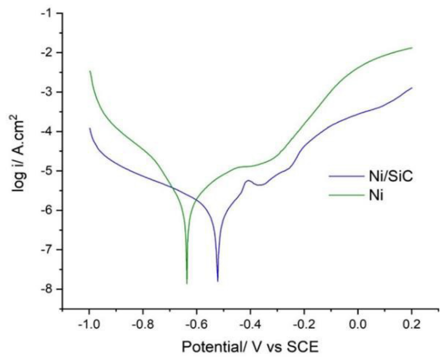

Fig. 4. Polarization curves of Ni and Ni/SiC composite coatings.

For further investigation of Ni and Ni/SiC coatings corrosion behavior, an EIS test was used in a solution of 3.5% NaCl. Nyquist curves of samples are shown in Fig. 5. The EIS parameters, including solution resistance (Rs), charge transfer resistance (Rct), and double-layer capacitance (CPEdl), were calculated using ZView software and listed in Table 3.

Table 3
EIS data obtained for the coatings.

Sample	Rs (Ω.cm^2)	CPEdl	Rct (Ω.cm^2)
Ni	13.11	7.24×10^{-6}	15094
Ni/SiC	14.24	1.16×10^{-7}	29323

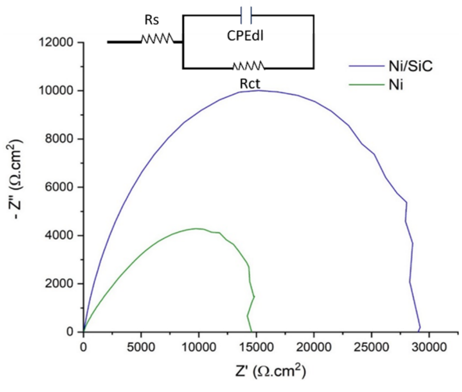

Fig. 5. Nyquist curves of Ni and Ni/SiC composite coatings.

It can be observed that due to the constant composition of the testing solution, the Rs values are for both samples. However, the Rct and CPEdl values for the composite sample increased and decreased, respectively, compared to the pure Ni coating. The increase in Rs and the decrease in CPEdl indicate an improvement in the corrosion resistance of the composite sample.

In both samples, the Nyquist curves are semicircles with one capacitor ring. In the composite sample, the diameter resistance and the area under curve are larger compared to the pure Ni coating, which indicates the improvement of corrosion resistance for the composite sample due to the addition of ceramic nanoparticles.

The incorporation of SiC nanoparticles into a Ni matrix composite can offer several benefits, including improved corrosion resistance. Here are a few reasons why the corrosion resistance of Ni/SiC composites is enhanced in the presence of SiC nanoparticles:

1. Passivation effect: SiC nanoparticles can form a protective layer on the surface of the composite material, acting as a barrier between the corrosive environment and the underlying nickel matrix. This passivation layer can inhibit the diffusion of corrosive species, such as ions or oxygen, and reduce their interaction with the Ni matrix, thus improving corrosion resistance [16,17].
2. Enhanced surface area: The addition of SiC nanoparticles increases the surface area of the composite material. The increased surface area provides more sites for the formation of the protective oxide layer, such as nickel oxide (NiO), which can act as a barrier against corrosion. The oxide layer formed on the SiC nanoparticles can also act as a corrosion inhibitor by reducing the exposure of the underlying Ni matrix to the corrosive environment [16,18].
3. Galvanic corrosion suppression: SiC nanoparticles have a high electrical conductivity compared to the Ni matrix. When the composite material is exposed to a corrosive environment, the SiC nanoparticles can act as cathodic sites, attracting corrosive species and preventing them from reaching the anodic Ni sites. This mechanism reduces the galvanic coupling between the SiC nanoparticles and the Ni matrix, suppressing galvanic corrosion. In the other hand, mechanism that can increase the corrosion resistance of nanocomposite coating is the high electrical conductivity of SiC particles, which reduces the possibility of cathodic reaction on the surface and prevents the formation of galvanic cells. Also, SiC particles act as hole fillers and physical barriers and prevent the penetration of corrosive liquid as much as possible [19].
4. Mechanical reinforcement: The incorporation of SiC nanoparticles into the Ni matrix can enhance the mechanical properties of the composite, such as hardness and wear resistance. Improved mechanical properties can indirectly contribute to better corrosion resistance by reducing the likelihood of corrosion initiation, such as surface cracks or defects, and providing better protection against mechanical damage that can expose the underlying Ni matrix to the corrosive environment [20,21]. On the other words, the increased hardness and improved mechanical properties of the composite coating reduce the likelihood of crack formation and surface defects. This reduction in defects limits the pathways for corrosive agents to penetrate the coating, thereby improving corrosion resistance.

4. Conclusion

In this study, a Ni/SiC composite coating was fabricated using the ultrasonic-assisted electrodeposition method. The effect of SiC nanoparticle incorporation on the microstructural, mechanical, and electrochemical properties of the Ni coating was then investigated.

The results indicated that the preferred orientation of the composite sample shifted from the (200) plane to the (111) plane compared to pure Ni. Moreover, the grain size decreased from 35 nm to 22 nm. For the composite sample, microhardness and Young's modulus increased by 45% and 46%, respectively, compared to the pure Ni coating, due to the reduction in grain size and the dispersion strengthening effect. Also, the presence of nanoparticles acted as barriers against corrosion attacks and increased the polarization resistance from 21376 to 52945 $\Omega.cm^2$.

Author contributions

Hossein Norouzi Heravan: Writing—Original Draft Preparation, Performed the analysis, **Yousef Zandi:** Writing— Original Draft Preparation, Writing—Review and Editing, Supervision.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

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