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Electrodeposition of Homogeneous and Functionally Graded Ni–Co/SiC Nanostructured Coatings: Erosion, Wear, and Corrosion Behavior

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Highlights

- Functionally graded Ni–Co/SiC coatings exhibit 40% higher adhesion strength and approximately twofold greater wear resistance compared with homogeneous coatings.
- A graded SiC distribution ranging from 0 to 6 wt.% enhances interfacial bonding, hardness, and corrosion resistance.
- The Ni–Co/SiC tribolayer coating promotes stable sliding wear behavior, thereby significantly improving durability in industrial environments.

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Abstract

In this study, nanostructured homogeneous and functionally graded Ni–Co/SiC coatings were fabricated on aluminum substrates by electrodeposition using a square pulse current. The functionally graded coating was produced by continuously varying the SiC particle concentration in the electrolyte from 0 to 40 g/L, resulting in a graded particle distribution throughout the coating thickness. The microstructure and morphology were characterized using scanning electron microscopy and X-ray diffraction. The mechanical and electrochemical properties were evaluated through microhardness measurements, T-peel adhesion testing, pin-on-disk wear testing, erosion testing, and potentiodynamic polarization and electrochemical impedance spectroscopy.

The results showed that the SiC content in the functionally graded coating gradually increased from 0 wt.% at the substrate interface to 6 wt.% at the surface. Compared with the homogeneous Ni–Co/SiC coatings, the functionally graded coating exhibited 40% higher adhesion strength and approximately twice the wear resistance. In addition, the functionally graded coating demonstrated enhanced corrosion resistance and overall mechanical performance, underscoring its potential for demanding industrial applications.

Keywords: Corrosion, Functionally graded coatings, Nanostructure, Ni-Co/SiC, Wear

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1. Introduction

Nanocomposite coatings have attracted significant attention in recent years because of their exceptional mechanical properties, including high hardness, self-lubrication, thermal stability, and resistance to oxidation, corrosion, and wear (Jiang et al., 2019; Wang et al., 2018). These characteristics make them highly attractive for a wide range of industrial applications. Various fabrication techniques have been investigated for producing nanocomposite coatings, including stir casting, spray deposition, physical vapor deposition, and electrolytic deposition (Roseana et al., 2021). Among these methods, electroplating is particularly advantageous due to its low cost, operational simplicity, and ability to produce dense coatings with excellent surface properties (Wang, 2004; Qin, 2008). Electroplated nanostructured coatings, especially those based on nickel and its alloys, are widely employed because of their superior wear and corrosion resistance, ease of fabrication, and high hardness (Wang, 2004; Qin, 2008). However, a major limitation of electroplated nanostructured coatings is their relatively poor adhesion strength, particularly when there is a significant mismatch in mechanical properties between the coating and the substrate (Wang, 2004; Qin, 2008). Such a mismatch can induce stress concentrations at the interface, which may reduce overall performance and promote coating delamination (Wang, 2004; Qin, 2008).

Functionally graded coatings are engineered with a gradual variation in composition and microstructure across the coating thickness, thereby reducing interfacial stresses and enhancing mechanical compatibility with the substrate (Leszek, 2020). In particular, functionally graded nanocomposite coatings, characterized by gradual changes in grain size, matrix composition, or reinforcement particle content, have demonstrated improved adhesion, toughness, and mechanical durability compared with homogeneous coatings (Lecina et al., 2009). The design of functionally graded coatings requires careful prediction of service requirements and corresponding gradients in material properties throughout the coating thickness (Allahyarzadeh, 2016; Vereschaka, 2019).

Functionally graded coatings can be fabricated using various techniques, including physical vapor deposition, chemical vapor deposition, electrophoresis, and electroplating (Wang, 2004; Pei, 2002). Among these approaches, electroplating is considered one of the most suitable methods for producing functionally graded coatings because it allows precise control over processing parameters and enables the fabrication of dense coatings with uniform composition (Wang, 2004; Lecina, 2009). By adjusting electroplating parameters such as current density, bath composition, and agitation or rotation speed, a controlled gradient in composition or microstructure can be established, facilitating the production of functionally graded coatings (Orlovskaja, 1998; Cavaliere, 2008). For nanocomposite functionally graded coatings, two key tunable parameters are the grain size of the metallic matrix and the concentration of reinforcing particles, such as SiC (Qin, 2008).

Qin et al. (2008) developed a nickel-based functionally graded coating with a controlled grain size gradient by gradually increasing the concentration of sodium saccharin, a grain-refining additive, in the electroplating bath. This strategy resulted in a gradual reduction in grain size from the coating–substrate interface, where grains were in the micrometer range, to less than 100 nanometers at the coating surface. The corresponding decrease in hardness from the surface toward the substrate indicates a smoother mechanical transition, which enhances mechanical compatibility and improves interfacial adhesion.

Previous studies have demonstrated that functionally graded coatings with gradients in grain size or reinforcement particle concentration exhibit significantly improved adhesion compared with homogeneous nanostructured coatings. This enhancement is primarily attributed to the reduction in mechanical property mismatch at the coating–substrate interface, which minimizes stress concentrations and strengthens interfacial bonding. In support of this concept, Cavaliere et al. (2008)

fabricated a Ni–W functionally graded coating by progressively increasing the current density during electroplating. This approach led to gradual grain refinement from approximately 100 nm near the substrate to about 30 nm at the coating surface. Tungsten, a well-established grain refiner in nickel-based matrices, played a critical role in achieving this microstructural evolution. Choi et al. (2008) further reported that higher tungsten content at elevated current densities suppresses grain growth, resulting in finer microstructures and enhanced mechanical performance.

In homogeneous composite coatings, increasing the particle concentration can significantly reduce adhesion strength. This deterioration is often attributed to the presence of ceramic particles at the coating–substrate interface, which disrupts metal–metal bonding, a primary mechanism governing strong interfacial adhesion. In contrast, functionally graded particle-reinforced coatings demonstrate substantially improved adhesion relative to homogeneous systems. This improvement arises from the gradual increase in particle concentration across the coating thickness, which mitigates interfacial discontinuities and mechanical incompatibilities. Several functionally graded particle-reinforced systems, including Ni/SiC, Ni/Al_2O_3, and Ni–Co/SiC coatings, have been successfully fabricated by progressively increasing the particle concentration in the electrolyte bath, current density, or electrolyte rotation speed during electrodeposition (Wang, 2004; Dong, 2006; Liu, 2008).

Kim et al. (1998) demonstrated that a gradual increase in SiC particle concentration in the electroplating bath produced a Ni/SiC coating in which the SiC content progressively increased with distance from the substrate interface. Bending tests indicated that these functionally graded coatings exhibited higher fracture resistance than homogeneous counterparts, while maintaining comparable wear behavior. Moreover, Wang et al. (2004) reported that functionally graded Ni/SiC coatings showed superior wear resistance compared with pure nickel coatings, which was attributed to the increased surface hardness resulting from SiC-enriched top layers. Additional studies have shown that cobalt alloying significantly enhances the mechanical properties and corrosion resistance of Ni/SiC coatings. The incorporation of cobalt into the Ni matrix improves both mechanical strength and corrosion performance. Furthermore, the dispersion of SiC nanoparticles, characterized by high hardness and thermal stability, within a Ni–Co matrix produces a composite with enhanced structural integrity, wear resistance, and durability under aggressive environments (Srivastava et al., 2012; Ma et al., 2020).

The present study aims to fabricate both homogeneous and functionally graded nanostructured Ni–Co/SiC coatings using pulse electroplating and to evaluate their adhesion strength, abrasion resistance, and corrosion performance. In contrast to previous investigations that primarily focused on homogeneous Ni–SiC systems, this work introduces a graded SiC particle distribution within a Ni–Co alloy matrix and directly compares it with a uniform coating structure. To the best of the authors' knowledge, this study is the first to systematically examine the combined effects of compositional grading and Ni–Co alloying, thereby representing a significant advancement in the development of durable, high-performance electroplated coatings.

2. Experimental procedures

2.1 Coating preparation

A Watts bath was employed to deposit both uniform and functionally graded (FG) Ni–Co/SiC coatings. The electrolyte was supplemented with varying amounts of nano-sized SiC powder, averaging 50 nm in diameter, cobalt sulfate, surface-activating agents, and grain-refining additives. The surface-activating agents included sodium dodecyl sulfate (SDS, $CH_3(CH_2)_{11}OSO_3Na$) and cetyltrimethylammonium bromide (CTAB, $C_{19}H_{42}BrN$), while sodium saccharin ($C_7H_4NNaO_3S \cdot 2H_2O$)

was used as the grain refiner. Electroplating parameters were selected as listed in Table 1. During the plating process, the concentration of SiC particles in the bath was gradually increased from 0 to 40 g/L.

Table 1

Electroplating parameters employed for the fabrication of functionally graded Ni–Co/SiC coatings

Cobalt sulfate	Sodium saccharin	SDS	current density	SiC
10 g/l	2 g/l	0.25 g/l	10 A/dm^2	0 to 40 g/l

2.2. Materials testing and characterization

2.2.1. Microstructural and phase analysis

The surface morphology and elemental composition of the coatings were investigated using field emission scanning electron microscopy (FESEM) coupled with energy-dispersive spectroscopy (EDS). Phase analysis was conducted by X-ray diffraction (XRD) using a Philips X'Pert MPD diffractometer with Cu-Kα radiation ($\lambda = 0.154$ nm). Data were acquired over a 2θ range of 30° to 100°, with a step size of 0.05° and a counting time of 1 second per step.

2.2.2. Adhesion test

Adhesion strength was evaluated using the T-Peel test (Figure 1), in which the coating and substrate were pulled in opposite directions. The force required to detach the coating from the substrate was recorded as the adhesion strength.

2.2.3. Wear and erosion test

Wear behavior was evaluated using a pin-on-disk abrasion test. The test parameters were set as follows: rotation speed of 300 rpm, sliding distance of 200 m, and rotation radius of 1 cm. The pin was fabricated from heat-treated 52100 AISI bearing steel (HRC 60) with dimensions of 6 mm diameter, 15 mm height, and a tip radius of 10 mm. An applied load of 5 N was used. Sample weights were measured with an accuracy of 0.0001 g before and after the test, and the difference was recorded as the weight loss. Wear rate curves were expressed as the ratio of weight loss to sliding distance.

Figure 1A presents the erosion test setup. In this test, a water jet containing 5% sand particles with an average size of 25 μm was directed onto the sample surface using a water pump. The test duration was 3 hours, and the weight loss of the samples was measured with an accuracy of 0.001 g.

2.2.4. Corrosion test

Corrosion behavior was evaluated using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) in a 3.5% NaCl solution at room temperature. Measurements were performed with an EG&G Model 273A three-electrode cell, with potentials referenced to a saturated calomel electrode (SCE). The scan rate for the polarization tests was 10 mV/s, and EIS measurements were conducted over a frequency range of 10^{-2} to 10^5 Hz.

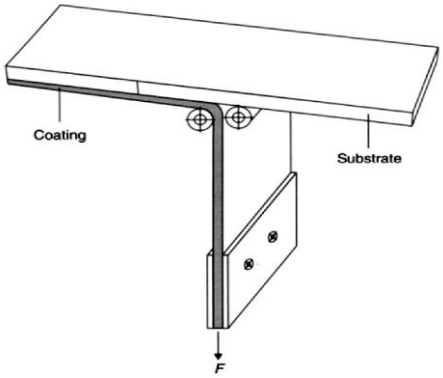

Figure 1

Schematic illustration of the T-Peel adhesion test setup used to evaluate coating–substrate adhesion strength (A) and image of the erosion test device (B).

3. Results and discussion

3.1. Morphology

Figures 2a–c illustrate the surface morphology of Ni–Co/SiC coatings fabricated with varying SiC particle concentrations in an electrolyte containing 2 g/L sodium saccharin. As observed, increasing the SiC concentration in the bath results in greater incorporation of particles on the coating surface. The cross-sectional view of the coating deposited at 30 g/L SiC (Figure 2d) confirms a uniform particle distribution throughout the layer, with no evidence of agglomeration. In contrast, Erb et al. (2002) reported significant agglomeration of SiC particles in Ni/SiC coatings produced from a bath containing 3 g/L sodium saccharin, which was attributed to the absence of surfactants. In the present study, the addition of sodium dodecyl sulfate (SDS) as an anionic surfactant likely played a critical role in preventing particle agglomeration and ensuring uniform dispersion within the coating matrix. SDS molecules adsorb onto the SiC particle surfaces, imparting a negative charge that causes mutual electrostatic repulsion between particles. This repulsion prevents particle clustering and allows for more even distribution within the coating.

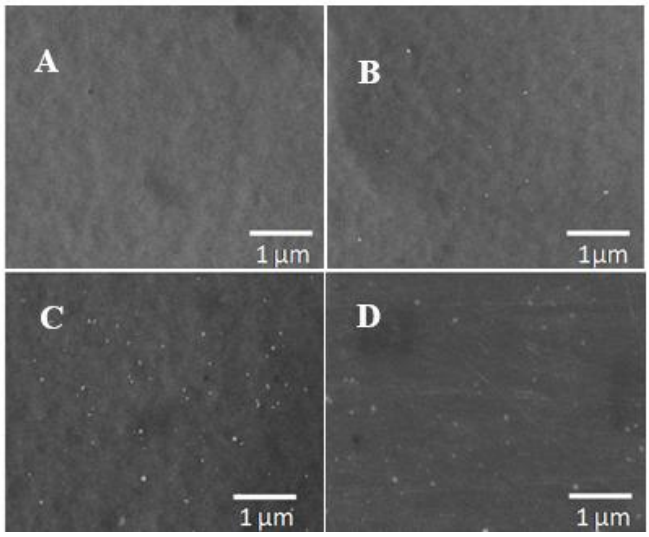

Figure 2

Surface morphology of Ni–Co/SiC coatings electroplated with varying SiC particle concentrations in the bath: (a) 0 g/L, (b) 15 g/L, and (c) 30 g/L; (d) cross-sectional view of the coating deposited at 30 g/L SiC, demonstrating uniform particle distribution.

Figure 3 presents the XRD patterns of Ni–Co/SiC coatings deposited from baths containing different concentrations of SiC nanoparticles. The Ni–Co matrix without SiC exhibits a dominant (200) crystallographic orientation, indicating a strong preferred texture in the absence of reinforcement particles. As the SiC concentration in the plating bath increases, however, a pronounced evolution in the coating texture is observed. Specifically, the intensity of the (200) peak progressively decreases, while the (111) reflection becomes more prominent. Moreover, the intensity of diffraction peaks at higher angles, particularly the (311) peak, increases significantly.

These texture changes are likely associated with modifications in the local deposition environment induced by the presence of SiC particles. One proposed mechanism involves the adsorption of H^+ ions onto the surfaces of SiC particles, which may perturb the local electric field and alter nucleation dynamics at the cathode–electrolyte interface (Lecina et al., 2009; Pavlatou et al., 2006). Such interactions can influence the growth kinetics and orientation of deposited metal grains, ultimately producing the observed variations in texture. The evolving texture not only reflects microstructural changes but may also affect the mechanical and corrosion properties of the coatings.

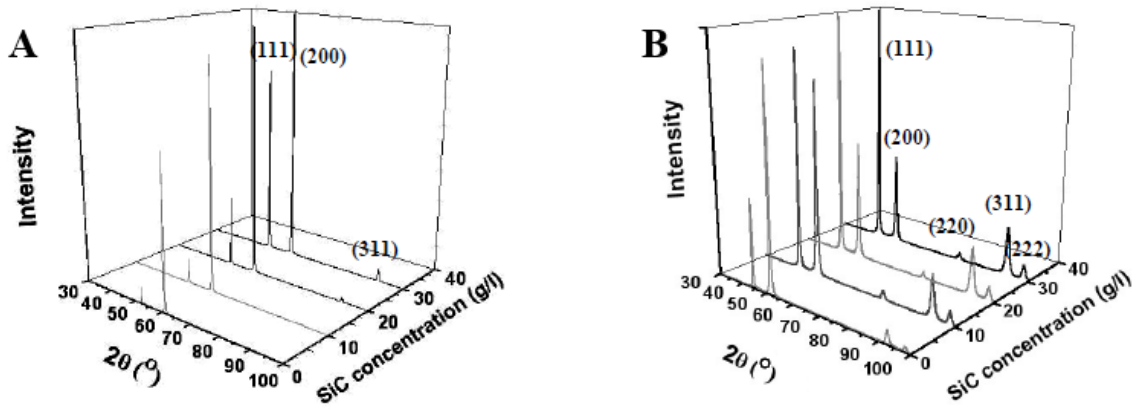

Figure 3

XRD patterns of Ni–Co/SiC coatings deposited with varying SiC particle concentrations in the plating bath

Table 2 summarizes the effect of SiC particle concentration and sodium saccharin content in the electrolyte on the coating composition, crystallite (grain) size, and the XRD I(111)/I(200) peak intensity ratio. As the SiC concentration in the plating bath increases from 0 to 40 g/L (samples E to K), the weight percentage of SiC incorporated into the coating rises progressively from 0 to 6.8 wt.%. Simultaneously, the crystallite size of the Ni–Co/SiC coatings decreases markedly, from 27 nm in the particle-free coating (E) to approximately 15 nm in the particle-reinforced coatings (H–K).

This grain size reduction is attributed to the synergistic effect of SiC nanoparticles and sodium saccharin as grain refiners. SiC particles serve as heterogeneous nucleation sites, while sodium saccharin restricts grain boundary mobility, both promoting nanostructure development. Moreover, the I(111)/I(200) intensity ratio increases sharply with higher SiC content, indicating a shift in preferred crystallographic orientation from (200) toward (111). This texture evolution suggests that SiC incorporation modifies growth kinetics at the coating–electrolyte interface, likely through localized adsorption phenomena or surface energy minimization mechanisms.

Interestingly, the control sample K*, prepared without sodium saccharin but exhibiting a comparable grain size, shows a similar I(111)/I(200) ratio to the high-SiC samples. This observation confirms that fine crystallite size alone does not fully account for the texture change. The combined influence of SiC concentration and saccharin is therefore critical for both grain refinement and orientation transition.

Table 2

Summary of the effects of SiC and sodium saccharin on coating composition, grain size, and crystallographic texture of Ni–Co/SiC coatings

Sample	SiC in bath (g/l)	Saccharin in bath (g/l)	SiC in coating (wt.%)	Coin coating (wt.%)	Crystallite size (nm)	$I_{(111)}/I_{(200)}$
E	0	2	0	15	27	0.42
F	10	2	1.5	14.5	23	1.20
G	20	2	3.2	14.9	16	2.10
H	30	2	4.8	14.4	15	2.03
K	40	2	6.8	14.7	15	2.03
K*	0	2	0	14.2	15	2.02

Figure 4 presents the cross-sectional morphology of the nanostructured functionally graded Ni–Co/SiC coating. The image reveals a clear microstructural gradient across the coating thickness. Moving away from the substrate–coating interface, an increasing concentration of SiC particles is observed, reflecting the gradual rise in particle content during electroplating. This gradient affects both the texture and grain structure of the coating. XRD analysis indicates a progressive intensification of the (111) diffraction peak relative to the (200) peak toward the coating surface, signifying a shift in preferred crystallographic orientation. Furthermore, the broadening of diffraction peaks and the smoother surface morphology in the upper layers suggest a reduction in grain size from the interface to the surface. These results confirm the successful formation of a functionally graded structure with refined microstructural characteristics.

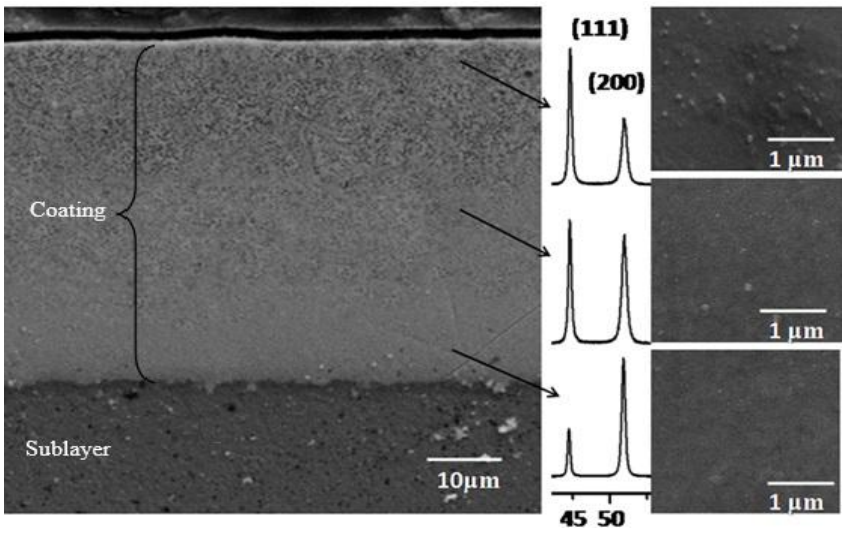

Figure 4

Cross-sectional morphology of the nanostructured functionally graded Ni–Co/SiC coating, showing layers at increasing distances from the interface, with corresponding XRD patterns (only the (111) and (200) peaks) and surface morphologies for each layer

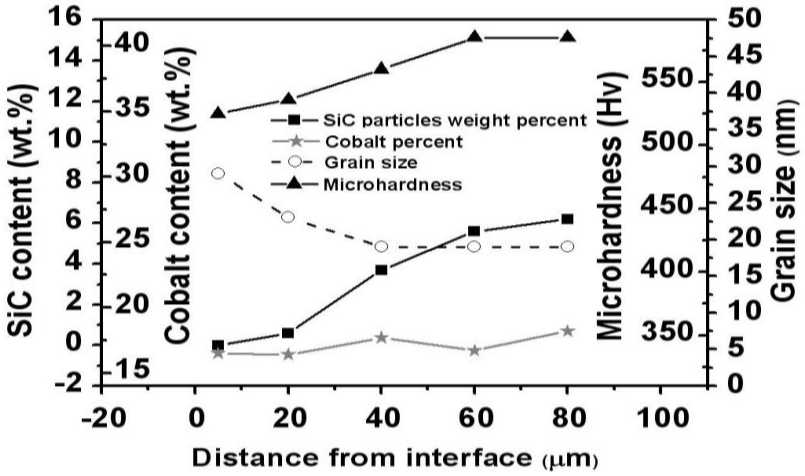

Figure 5

Variations in grain size, cobalt concentration, SiC particle content, and microhardness as a function of distance from the interface in the nanostructured functionally graded coating

Figure 5 illustrates the variations in grain size, cobalt content, SiC particle concentration, and microhardness as a function of distance from the substrate interface for the functionally graded (FG) Ni–Co/SiC coating. The grain size gradually decreases along the coating thickness, from the interface toward the surface, corresponding with the increasing incorporation of SiC particles and a slight rise in cobalt content.

The microhardness of the coating exhibits a modest but consistent increase, from approximately 540 to 575 HV, with increasing distance from the interface. This enhancement in hardness is primarily attributed to grain size reduction (Ma et al., 2020), in agreement with the Hall–Petch relationship. However, the relatively small increase in hardness indicates that the dispersion-strengthening effect of SiC particles is limited, likely due to their gradual and moderate incorporation rather than abrupt accumulation. Overall, these gradual compositional and microstructural variations contribute to a more uniform and mechanically robust graded coating structure.

3.2. Adhesion and tribo-mechanical performance

Table 3 presents the bond toughness values of homogeneous nanostructured Ni–Co/SiC coatings as a function of SiC particle concentration. The data indicate that increasing the SiC content in the bath reduces adhesion strength. This decline is primarily attributed to the accumulation of SiC particles at the coating–substrate interface, which disrupts metal–metal bonding. Instead, metal–ceramic bonds are formed, which are inherently weaker, thereby compromising interfacial adhesion (metal refers to the substrate and the coating matrix, while the ceramic phase refers to the SiC particles). Additionally, the increased presence of SiC particles promotes grain refinement in the coating. Although finer grains generally enhance mechanical hardness, they also introduce greater mismatch stresses at the interface, further reducing bond toughness.

In contrast, the functionally graded Ni–Co/SiC coating demonstrates significantly improved adhesion strength. This enhancement results from the gradual increase in particle concentration across the coating thickness, which preserves a SiC-free or low-SiC region near the interface. Consequently, strong metal–metal bonding is maintained adjacent to the substrate, minimizing interfacial stress and improving overall adhesion (Wang, 2004; Dong, 2006; Liu, 2008). The functionally graded structure effectively overcomes the limitations of homogeneous coatings, providing a more robust interface and enhanced durability under mechanical stress.

Table 3

Adhesive toughness values of homogeneous Ni–Co/SiC nanostructured coatings with varying SiC particle concentrations

Sample	Crystallite size (nm)	Bonding strength (J/m^2)
E (Ni-Co)	27	0.85×10^3
F (Ni-Co-1.5 wt.% SiC)	23	0.71×10^3
H (Ni-Co-4.8 wt.% SiC)	15	0.66×10^3
K (Ni-Co-6.8 wt.% SiC)	15	0.47×10^3
N functionally graded (Ni-Co-6.8 wt.% SiC)	15	0.77×10^3
K*	15	0.83×10^3

Figures 6 and 7 illustrate the average wear rate, friction coefficient, and erosion-induced weight loss of Ni–Co/SiC nanostructured coatings with varying SiC particle concentrations under a 5 N vertical load. Data for the functionally graded (FG) nanostructured coatings are also included for comparison.

As shown in Figure 6, increasing the SiC particle concentration in homogeneous nanostructured coatings reduces both the wear rate and friction coefficient. This improvement in wear performance is attributed to a moderate increase in surface hardness and the strengthening effect of SiC particles, which likely inhibit microcrack propagation and tribological damage. Additionally, SiC particles enhance hardness by refining the grain structure and acting as barriers to dislocation motion. They also reduce direct metal-to-metal contact during wear, thereby decreasing adhesive wear due to the inherently weaker metal–ceramic bonding relative to metal–metal bonding.

The functionally graded coating exhibits the lowest wear rate and friction coefficient overall, although the differences are only marginal compared to the homogeneous coating containing 8.6 wt.% SiC. This observation indicates that while high particle content is advantageous, the gradual variation of particle concentration in FG coatings provides an additional benefit by reducing interfacial stresses and improving structural integrity. The enhanced wear resistance of FG coatings is therefore not solely due

to increased hardness but also results from improved stress distribution and adhesion across the coating–substrate interface, which mitigates delamination and surface damage during wear.

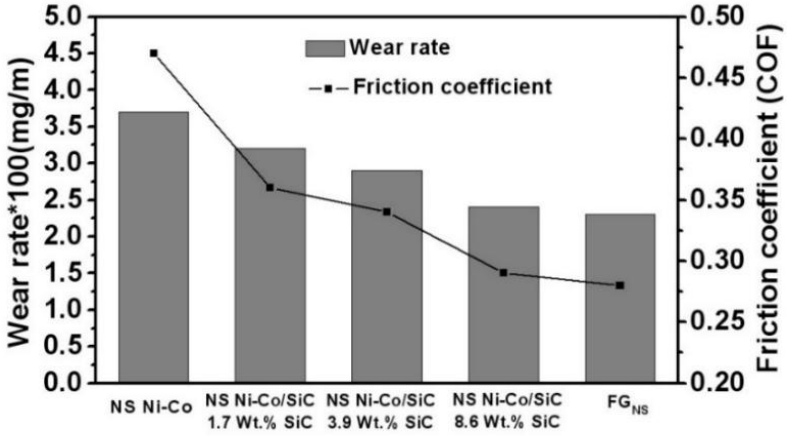

Figure 6

Variations in grain size, cobalt content, SiC particle concentration, and microhardness as a function of distance from the substrate interface in the nanostructured functionally graded coating

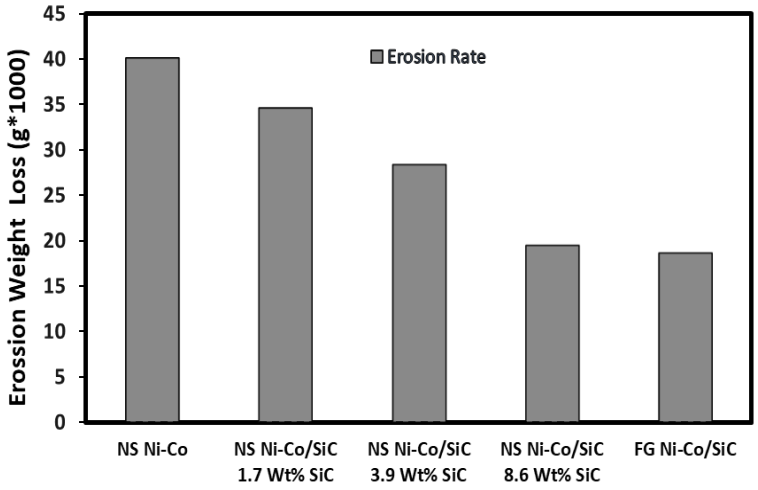

Figure 7

Erosion reduction of homogeneous nanostructured coatings at varying SiC particle concentrations and of nanostructured functionally graded coatings

Turning to Figure 7, erosion resistance exhibits a trend similar to that observed for wear, increasing with higher SiC content in homogeneous coatings. The erosion-induced weight loss decreases as the particle concentration rises, with the lowest loss observed at 8.6 wt.% SiC. Notably, the functionally graded (FG) coating demonstrates slightly superior erosion resistance compared to this homogeneous counterpart. This enhanced performance is attributed to the harder outer layers of the FG coating, which are better able to withstand the impact forces of erosive particles.

These results are consistent with previous studies on functionally graded Ni/SiC coatings (Hou, 2002), which showed that surface hardening and compositional grading improve erosion resistance. While homogeneous coatings with high SiC content exhibit significant improvements in both wear and erosion performance, FG coatings provide a more robust and balanced solution. Their unique structure

combines a hard surface layer with a gradual internal composition, enhancing mechanical integrity and resistance to damage.

Importantly, FG coatings simultaneously achieve high adhesion strength at the substrate interface and low wear rates at the surface, a combination that is challenging to obtain in homogeneous coatings. These characteristics make FG coatings particularly attractive for industrial applications, where components are frequently exposed to both mechanical stress and surface degradation. Consequently, functionally graded particle-reinforced coatings represent a superior alternative to conventional homogeneous coatings in demanding service environments.

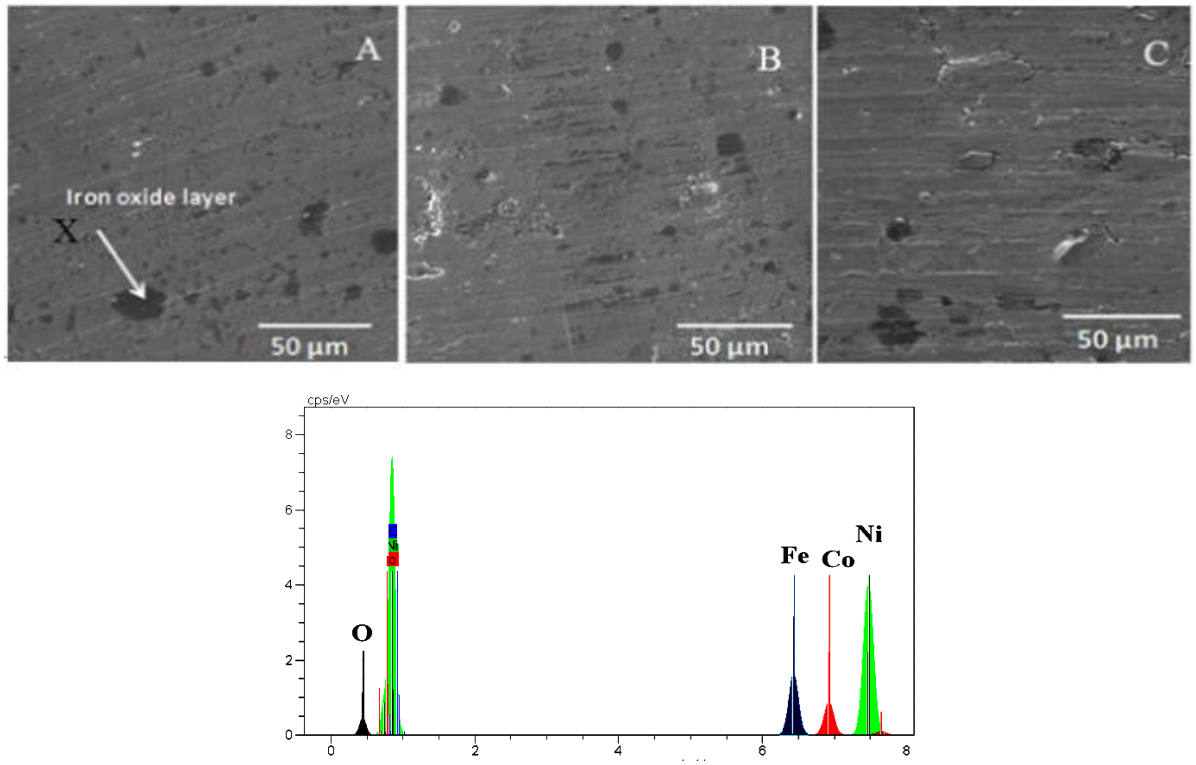

Figure 8

Backscattered electron SEM images of worn surfaces under a 5 N normal load: (A) nanostructured functionally graded Ni–Co/SiC coating, (B) homogeneous nanostructured Ni–Co/SiC coating with 6.8 wt.% SiC, (C) homogeneous nanostructured Ni–Co coating without SiC, and (D) EDS spectrum corresponding to point X on the tribological layer shown in image A.

The worn surface morphologies of the nanostructured coatings are presented in Figure 8, providing insight into the underlying wear mechanisms. Figures 8A–C show backscattered electron (BSE) SEM images of the worn surfaces of the functionally graded (FG) coating, the homogeneous Ni–Co/SiC coating with 6.8 wt.% SiC, and the pure Ni–Co coating, respectively, all tested under a 5 N load. The smoother surfaces and finer grooves observed in Figures 8A and 8B, compared to Figure 8C, indicate reduced adhesive and abrasive wear in coatings reinforced with SiC nanoparticles. This confirms the beneficial effect of SiC in enhancing tribological performance by minimizing direct metal-to-metal contact.

Notably, dark scattered particles are visible on the worn surfaces of the FG and SiC-containing coatings (Figures 8A and 8B), suggesting the formation of a tribological layer. The EDS spectrum at point X in Figure 8A, shown in Figure 8D, reveals the presence of nickel, cobalt, iron, and oxygen, with approximate compositions of 5.59 wt.% Ni, 9.10 wt.% Co, 1.22 wt.% Fe, and 7.5 wt.% O. The detection

of iron and oxygen strongly indicates the formation of iron oxide particles, likely resulting from the transfer and oxidation of debris from the steel counterface during sliding. Such tribological layers, composed of compacted debris and oxides, act as solid lubricants that reduce both the wear rate and friction coefficient (Holmberg, 1998). These observations are consistent with findings reported by Choi (2008) for Ni/SiC coatings subjected to similar wear conditions.

The dominant wear mechanism for both homogeneous and FG nanostructured Ni–Co/SiC coatings appears to be sliding wear, facilitated by the formation of a self-lubricating tribo-layer that mitigates severe surface damage and prolongs coating lifespan.

3.3. Corrosion behavior

Figure 9 presents the potentiodynamic polarization curves of nanostructured Ni–Co/SiC coatings with varying SiC particle concentrations. For comparison, the polarization behavior of the nanostructured functionally graded (FG) coating is also included. The corresponding electrochemical parameters—including corrosion potential (E_{corr}), corrosion current density (i_{corr}), anodic (β_a) and cathodic (β_c) Tafel slopes, and polarization resistance (R_p)—are summarized in Table 4 for both homogeneous and FG coatings.

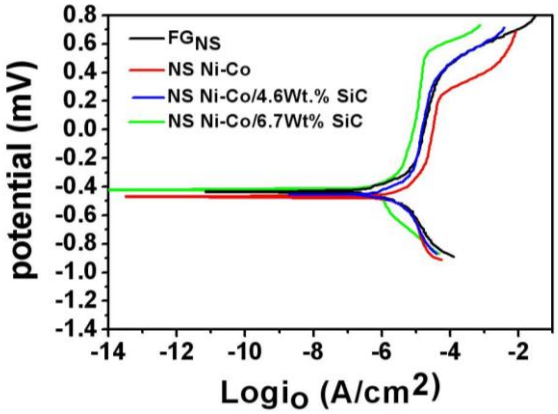

Figure 9

Potentiodynamic polarization curves of nanostructured Ni–Co/SiC coatings with varying SiC particle concentrations, including the functionally graded coating, in 3.5 wt.% NaCl solution at ambient temperature

All homogeneous coatings exhibit a well-defined passive region, indicating the formation of protective surface oxide layers. As the SiC particle concentration increases, corrosion resistance improves, evidenced by a shift of the passive layer breakdown potential toward more noble values and a reduction in both corrosion current density and passive current. These trends suggest that higher SiC incorporation enhances the stability and protective nature of the passive film. The improved passivation behavior can be attributed to two main factors. First, the nanostructured grains promote rapid passive film formation due to their high density of grain boundaries, which serve as favorable nucleation sites for oxide growth (Meng, 2008; Mishra, 2004). Second, the embedded SiC particles reduce the electrochemically active surface area, limiting localized corrosion sites and stabilizing the passive film.

The FG coating exhibits corrosion resistance comparable to or slightly exceeding that of the homogeneous coatings. As shown in Table 4, the corrosion current density of the FG coating lies between that of the homogeneous Ni–Co coating and the Ni–Co/SiC coating with similar surface microstructure, indicating that the incorporation of SiC particles in the FG structure contributes to enhanced corrosion performance. However, the corrosion current of the FG coating is slightly higher than that of the homogeneous coating containing 8.6 wt.% SiC, likely due to the graded distribution of

SiC particles. In the FG coating, the lower layers near the substrate contain fewer particles, providing slightly less protection and allowing limited pit initiation. Nonetheless, the FG structure achieves a favorable balance between surface protection and interfacial integrity, making it a promising strategy for simultaneously enhancing corrosion resistance and mechanical performance in advanced coating systems.

Table 4

Electrochemical parameters including corrosion potential (E_{corr}), corrosion current density (i_{corr}), anodic Tafel slope (β_a), cathodic Tafel slope (β_c), polarization resistance (R_p), passivation current (i_p), and breakdown potential (E_b) for nanostructured Ni–Co/SiC coatings with different SiC particle concentrations, including the functionally graded coating for comparison

Sample	E_{corr} (V)	i_{corr} (μA/cm²)	β_c (V/ μA/cm²)	β_a (V/ μA/cm²)	R_p (kΩ)	E_b (V)	i_p (μA/cm²)
E (Ni-Co)	-0.481	0.908	0.072	0.092	19.31	0.201	0.211
H (Ni-Co-4.8 wt.% SiC)	-0.465	0.241	0.063	0.075	61.68	0.381	0.167
K (Ni-Co-6.8 wt.% SiC)	-0.421	0.158	0.061	0.072	90.75	0.561	0.123
N functionally graded (Ni-Co-6.8 wt.% SiC)	-0.441	0.199	0.053	0.071	66.21	0.395	0.169

Figure 10 displays the corroded surface morphologies of nanostructured Ni–Co and Ni–Co/SiC coatings after electrochemical testing. It is evident that both the number and size of corrosion pits are significantly reduced in the composite coatings containing SiC particles. This reduction in pitting clearly indicates enhanced corrosion resistance with increasing particle content.

The improved performance is attributed to the role of SiC particles in minimizing the electrochemically active surface area and hindering the initiation and propagation of localized corrosion. Similar observations have been reported by other researchers (Chen, 2005; Aruna, 2006), who noted that ceramic particles embedded in the metal matrix enhance the overall electrochemical stability of the surface. Furthermore, the uniform distribution of SiC particles across the coating surface raises the local electrochemical potential, thereby reducing the driving force for pit growth. Since the advancement of corrosion pits is accelerated at sites of lower potential—typically found at pit tips—this increase in surface potential makes pit propagation more difficult and slows overall degradation. Consequently, the presence of SiC particles acts as both a physical and electrochemical barrier to localized corrosion.

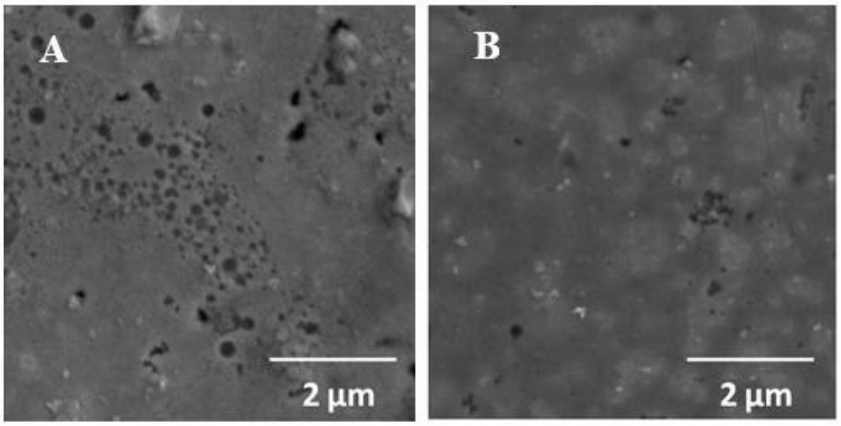

Figure 10

Surface images of corroded nanostructured coatings after electrochemical testing in 3.5 wt.% NaCl solution: (A) nanostructured Ni–Co coating, (B) nanostructured Ni–Co/SiC coating containing 6.0 wt.% SiC particles

4. Conclusions

This study investigated the mechanical, tribological, and corrosion behaviors of homogeneous and functionally graded Ni–Co/SiC nanostructured coatings fabricated via electroplating with varying SiC particle concentrations. The results highlighted the critical role of particle distribution and structural gradation on the performance characteristics of the coatings. The main conclusions are summarized as follows:

1. Increasing the SiC particle concentration in homogeneous coatings led to a significant improvement in wear and corrosion resistance. This enhancement was primarily attributed to increased surface hardness, grain refinement, and the barrier effect of hard ceramic particles. However, the incorporation of particles at the coating–substrate interface adversely affected adhesion strength, as ceramic particles disrupted strong metal–metal bonding.
2. The functionally graded Ni–Co/SiC coating exhibited superior performance compared to homogeneous coatings, combining high wear resistance with enhanced adhesion strength. The absence of SiC particles at the interface facilitated strong bonding with the substrate, while the particle-rich upper layers contributed to improved hardness and tribological behavior.
3. The dominant wear mechanism in both homogeneous and FG coatings was identified as sliding wear, associated with the formation of a tribological layer composed of iron oxide particles from the counterface. This layer acted as a solid lubricant, reducing both friction and wear during operation.

Overall, functionally graded Ni–Co/SiC coatings represent a promising approach for applications requiring a balance of high adhesion and surface durability, particularly in wear- and corrosion-intensive environments.

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Nomenclature

E_b	Breakdown potential
E_{corr}	Corrosion current density
i_p	Passivation current
R_p	Polarization resistance
β_a	Anodic Tafel slopes
β_c	Cathodic Tafel slopes

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