

Article

Effect of Electroless Ni Plating Time on the Surface Evolution and Electrochemical Behavior of Al–cBN Composites

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Abstract

Al-based composites have attracted significant attention in the aerospace, automotive, and electronic industries due to their lightweight characteristics, high specific strength, and superior thermal conductivity. Although Al–cBN composites exhibit enhanced mechanical and wear properties, galvanic interactions between the Al matrix and carbon-based reinforcements can accelerate localized corrosion and reduce electrochemical stability in chloride-containing environments. To improve these limitations, Ni coating has been considered an effective surface modification method because of its high corrosion resistance and electrochemical stability. However, investigations on the surface and electrochemical behavior of Ni-coated Al–cBN composites remain limited. In this study, the surface characteristics and electrochemical behavior of Ni-plated Al–cBN composites were systematically investigated. Surface morphology and microstructural evolution were analyzed using FE-SEM, while crystallographic characteristics and phase evolution were examined through XRD analysis. In addition, electrochemical properties were evaluated using OCP and potentiodynamic polarization measurements. The results revealed that the specimen plated for 600 s exhibited a corrosion potential shift from -0.92 V to -0.38 V, together with a significant reduction in corrosion current density, indicating improved electrochemical stability and corrosion resistance due to the formation of a dense Ni coating layer. These results demonstrate that electroless Ni plating is an effective surface modification technique for enhancing the corrosion resistance and electrochemical stability of Al–cBN composites.

Keywords: Al–cBN-based composite; Ni plating; electrochemical behavior; surface characterization



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1. Introduction

Al-based composites have been widely utilized in various industries, including aerospace, automotive, electronic components, and energy systems, due to their excellent lightweight characteristics, high specific strength, and superior thermal conductivity [1,2]. These materials have attracted considerable attention as next-generation lightweight structural materials because they can achieve excellent mechanical properties while maintaining

significantly lower density compared with conventional steel materials [3,4]. Recently, Al–cBN composites reinforced with cubic boron nitride (cBN) particles have demonstrated enhanced wear resistance and improved mechanical stability, thereby expanding their potential industrial applications [5,6]. cBN reinforcements possess excellent thermal stability, high hardness, and superior electrical insulation properties, making them promising candidates for the development of high-performance composite systems.

Al–cBN composites offer several advantages, including high strength, enhanced hardness, and improved tribological properties resulting from the incorporation of cubic boron nitride (cBN) reinforcements [7,8]. However, interfacial instability between the Al matrix and cBN particles can occur under corrosive environments due to differences in electrochemical behavior and thermal expansion characteristics [9,10]. The passive oxide layer on the Al surface can be easily damaged in chloride-containing environments, leading to accelerated localized corrosion and degradation at the matrix–reinforcement interface [11,12]. These phenomena can reduce long-term structural stability and electrochemical reliability, thereby limiting the practical industrial applications of Al–cBN composites.

To overcome these limitations, various surface modification technologies have been actively investigated, among which Ni plating has been considered an effective approach due to its excellent corrosion resistance, chemical stability, and interfacial compatibility [13,14]. The Ni coating layer can suppress surface oxidation by preventing direct contact between the electrolyte and the Al matrix while simultaneously improving the interfacial bonding characteristics between the Al matrix and cBN reinforcements [15,16]. In addition, Ni possesses relatively high hardness and wear resistance, which can contribute to enhancing the mechanical stability and durability of the composite surface [17,18]. Therefore, Ni plating has attracted considerable attention as an effective strategy for simultaneously improving the interfacial stability, surface durability, and corrosion resistance of Al–cBN composites.

Previous studies have reported various improvements in surface hardness, tribological behavior, and corrosion resistance through the application of Ni coatings on Al alloys and metallic composites [19,20]. Several studies have demonstrated that electroless Ni coatings can reduce surface pores and defects while suppressing corrosion reactions by increasing charge transfer resistance [19,21]. Furthermore, electrochemical analyses have revealed that Ni coatings can decrease corrosion current density and promote more stable corrosion potentials [22,23]. However, most previous investigations have mainly focused on conventional Al alloys or monolithic metallic systems, while systematic studies on the interfacial characteristics and electrochemical behavior of Ni-coated Al–cBN composites remain scarce.

In particular, comprehensive investigations on the correlation between microstructural evolution, crystallographic characteristics, and electrochemical behavior in Ni-coated Al–cBN composites have rarely been reported. Most previous studies have primarily focused on conventional Al alloys or monolithic metallic systems, whereas systematic investigations of electroless Ni-plated Al–cBN composites remain limited. Furthermore, insufficient attention has been given to the relationship between coating growth behavior, coating continuity, and electrochemical stability under corrosive electrolyte environments.

Therefore, in this study, electroless Ni plating was applied to the surface of Al–cBN composites, and the resulting surface characteristics and electrochemical behavior were systematically investigated. Surface morphology, coating evolution, and microstructural characteristics were analyzed using FE-SEM, while phase evolution and crystallographic changes were examined through XRD analysis. Furthermore, OCP and potentiodynamic polarization tests were conducted to evaluate the electrochemical properties of the specimens. The novelty of this work lies in the systematic investigation of the coating evolution, crystallographic characteristics, galvanic corrosion behavior, and electrochemical stability

of electroless Ni-plated Al–cBN composites as a function of plating time. In addition, the relationship between coating continuity and corrosion resistance was clarified to provide insights into the development of corrosion-resistant Al–cBN composites for thermal management applications.

2. Experimental Method

2.1. Materials

Al–cBN composites were fabricated to investigate the effect of Ni plating on the surface characteristics and electrochemical behavior of Al-based composites. Commercial Al 1050 was selected as the matrix material because of its low density, high thermal conductivity, and excellent formability [14,15]. Cubic boron nitride (cBN) powder with an average particle size of 15 μm was used as the reinforcement phase owing to its high hardness, excellent thermal stability, and superior wear resistance [24]. The reinforcement content was fixed at 10 wt.%.

To fabricate the composites, Al 1050 (99.5 wt.% Al, 0.4 wt.% Fe, and 0.07 wt.% Zn) ingots were melted in a crucible furnace above the melting temperature (700 °C) of aluminum. cBN powder was added to the molten Al and mechanically stirred to promote homogeneous dispersion of the reinforcement particles throughout the molten matrix. Continuous stirring was performed to minimize particle agglomeration and improve the distribution uniformity of cBN within the Al melt. After achieving a uniform Al–cBN slurry, the molten composite was cast and allowed to solidify under ambient conditions.

The fabricated specimens were machined to dimensions of 15 mm $\times$ 15 mm $\times$ 5 mm and subsequently used for surface characterization and electrochemical evaluation. The overall experimental procedure is illustrated in Figure 1.

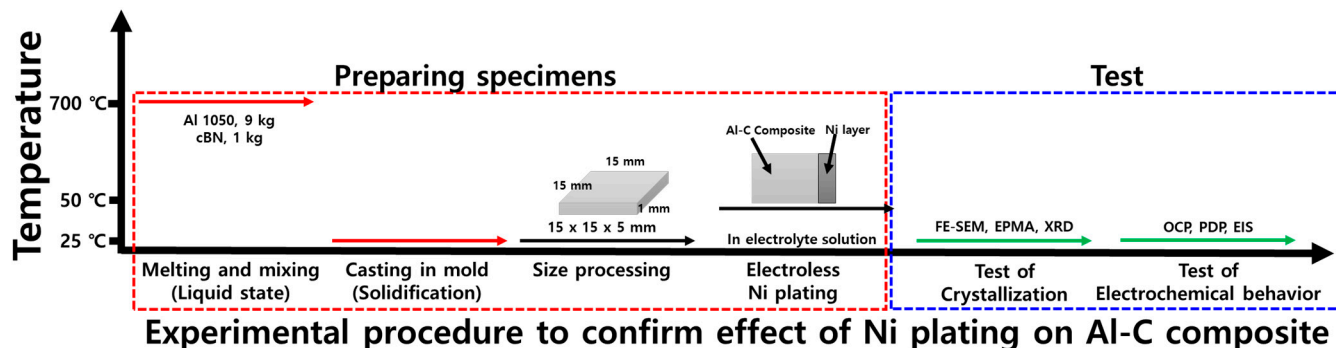


Figure 1. Schematic diagram of the experimental procedure for fabrication, Ni plating process, and electrochemical analysis of the Al–cBN composite.

2.2. Ni Plating

Prior to the Ni plating process, grinding and cleaning procedures were performed to remove surface impurities and native oxide layers from the specimens. The specimen surfaces were sequentially polished using SiC papers of various grit sizes, followed by ultrasonic cleaning in ethanol and distilled water. After the pretreatment process, Ni plating was conducted to form a uniform Ni coating layer on the surface of the Al–cBN composites. To investigate the initial growth behavior and surface evolution of the coating layer, the plating times were controlled at 0 s, 60 s, 120 s, 180 s, 240 s, 300 s, and 600 s.

The Ni plating electrolyte was prepared using 270 g/L of $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$, 45 g/L of $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, and 35 g/L of H_3BO_3 dissolved in deionized (DI) water [19,20]. The plating process was carried out at 50 °C under continuous stirring at 50 rpm to ensure uniform electrolyte distribution and stable coating formation on the specimen surface. After plating,

the coated specimens were thoroughly rinsed with distilled water, dried under ambient conditions, and subsequently used for further microstructural and electrochemical analyses.

2.3. Analysis of Surface

The surface morphology, cross-section images, and coating layer characteristics of the fabricated composites were observed using field-emission scanning electron microscopy (FE-SEM, SUPRA 40VP system, Zeiss, Oberkochen, Germany). FE-SEM analysis was performed to investigate the surface evolution and growth behavior of the Ni coating layer according to plating time. In addition, the distribution of surface defects, pores, and cBN particle dispersion behavior was examined to evaluate the uniformity and compactness of the coating layer. Furthermore, Energy Dispersive Spectroscopy (EDS, Bruker, Berlin, Germany) analysis coupled with FE-SEM was conducted to investigate the elemental distribution and compositional characteristics of the composite surface and interfacial regions. The thickness of the Ni-plated layer was calculated using glow discharge spectroscopy (GDS, Horiba Jobin Yvon, JY-10000 RF, Palaiseau, France). GDS shows the results of depth profiling from the surface to 5 μm . The calculated area is 1 cm^2 , and the scan rate is 0.1 $\mu\text{m}/\text{min}$ by 400 W.

Furthermore, X-ray diffraction (XRD, Bruker D8 Advance, Karlsruhe, Germany) analysis was conducted to investigate the crystallographic characteristics and phase evolution of the specimens before and after Ni plating [8,25]. The XRD measurements were carried out within a diffraction range of 10–80° using Cu-K α radiation. Through the XRD analysis, the formation of Al matrix phases, Ni-related phases, and cBN-related diffraction peaks was identified. In particular, changes in diffraction peak intensity, peak overlap behavior, and preferred orientation caused by the Ni coating process were analyzed in detail. Based on these results, the effects of Ni plating on the surface structural evolution and phase formation behavior of the Al–cBN composites were systematically evaluated. To ensure the reliability and reproducibility of the experimental results, all surface characterization analyses (FE-SEM, EDS, and GDS) and crystallographic analyses (XRD) were repeated five times under identical experimental conditions.

2.4. Analysis of Electrochemical Behavior

The electrochemical behavior of the specimens was evaluated using a potentiostat (VersaSTAT 4.0, AMETEK, Inc., Berwyn, PA, USA) through OCP (Open Circuit Potential) and potentiodynamic polarization measurements [26,27]. All electrochemical experiments were conducted using a conventional three-electrode system consisting of a working electrode (WE, specimens, 1 cm^2), reference electrode (RE), saturated calomel electrode (KCl), and counter electrode (CE, Pt mesh 20 $\times$ 20 mm) [28]. The fabricated Al–cBN composites and Ni-plated specimens were employed as the working electrodes, while electrochemical corrosion behavior was investigated in a 3.5 wt.% NaCl electrolyte solution at room temperature to simulate a chloride-containing corrosive environment.

The OCP measurements were performed for 1 h to evaluate the electrochemical stability and time-dependent potential variation behavior of the specimens [17,29]. The stabilization tendency of the open circuit potential was analyzed to investigate the formation and stability of passive surface films before electrochemical polarization testing. Potentiodynamic polarization tests were conducted in the potential range from -1.8 V to 0.6 V for the base materials and from -1.8 V to 0.0 V for the electroless Ni-plated specimens at a scan rate of 1.67 mV/s [30,31]. Through polarization analysis, the corrosion potential (E_{corr}), corrosion current density (I_{corr}), passivation characteristics, and localized corrosion behavior were systematically evaluated.

Furthermore, the influence of the Ni coating layer on anodic dissolution behavior, passive film stability, and corrosion suppression characteristics was comparatively analyzed according to plating time. Based on these electrochemical analyses, the effect of Ni plating on the electrochemical stability, interfacial durability, and corrosion resistance of the Al–cBN composites was comprehensively evaluated. All electrochemical measurements were performed five times under identical experimental conditions to ensure the reliability, reproducibility, and statistical consistency of the obtained results.

3. Results

3.1. Cast Al–cBN Composite

FE-SEM analysis is useful for observing microstructural characteristics and is widely utilized for microstructural evaluation of composite materials. Figure 2 presents the microstructural analysis results of the cast Al–cBN composite. When the microstructure was observed at a magnification of $1000\times$, the cast Al–cBN composite exhibited distinguishable heterogeneous microstructural regions. In particular, bright Al-rich regions and relatively dark cBN-containing regions were observed. The heterogeneous distribution of the reinforcement phase within the Al matrix can contribute to improving the mechanical strength by restricting dislocation movement and enhancing load transfer behavior. However, non-uniform interfacial distribution and localized structural heterogeneity may adversely affect the long-term electrochemical stability and corrosion resistance of the composite in chloride-containing environments [32,33].

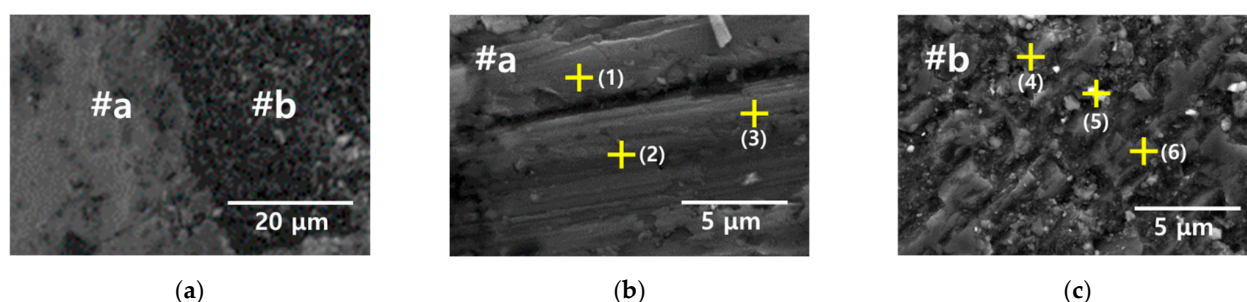


Figure 2. FE-SEM images of the cast Al–cBN composite before Ni plating: (a) low-magnification image ($\times 1000$), (b) high-magnification image ($\times 50,000$) of region (#a), and (c) high-magnification image ($\times 50,000$) of region (#b).

To investigate the elemental distribution and interfacial characteristics of the cast Al–cBN composite, compositional analysis was conducted at specific regions, and the results are summarized in Table 1. The compositional analysis at region #a revealed an Al content higher than 99.0 wt.%, indicating the Al-rich matrix region. In contrast, the analysis at region #b showed a relatively lower Al content together with increased B and N elemental signals originating from the cBN reinforcement phase. These compositional differences indicate the heterogeneous distribution of the cBN reinforcement within the Al matrix and suggest the formation of distinct interfacial regions in the Al–cBN composite system [34,35].

Table 1. EDS compositional analysis results of the cast Al–cBN composite at the selected regions indicated in Figure 2.

wt.%	(1)	(2)	(3)	(4)	(5)	(6)
Al	99.4 ± 0.2	99.6 ± 0.3	99.4 ± 0.5	88.3 ± 1.1	87.9 ± 1.2	88.8 ± 1.4
Fe	0.5 ± 0.2	0.4 ± 0.3	0.6 ± 0.5	0.2 ± 0.2	0.2 ± 0.2	0.1 ± 0.2
B	-	-	-	5.7 ± 0.9	5.9 ± 0.9	5.5 ± 0.8
N	-	-	-	5.8 ± 0.8	6.0 ± 0.8	5.6 ± 0.9

XRD analysis was conducted to investigate the phase evolution and crystallographic characteristics of the Al–cBN composite system before and after electroless Ni plating. Figure 3 presents the representative diffraction peaks of the Al matrix, cBN reinforcement phase, and electroless Ni coating layer. The cBN phase exhibited characteristic diffraction peaks corresponding to the cubic boron nitride crystal structure, confirming the successful incorporation of the reinforcement phase within the composite system. In the Al phase, characteristic FCC diffraction peaks corresponding to Al (111), Al (200), Al (220), and Al (311) were observed at approximately 38.5°, 44.7°, 65.1°, and 78.2°, respectively [11,12]. In addition, the electroless Ni coating layer exhibited characteristic diffraction peaks of Ni (111), Ni (200), and Ni (220) at approximately 44.5°, 51.8°, and 76.4°, confirming the successful formation of the Ni coating layer on the composite surface [19,36].

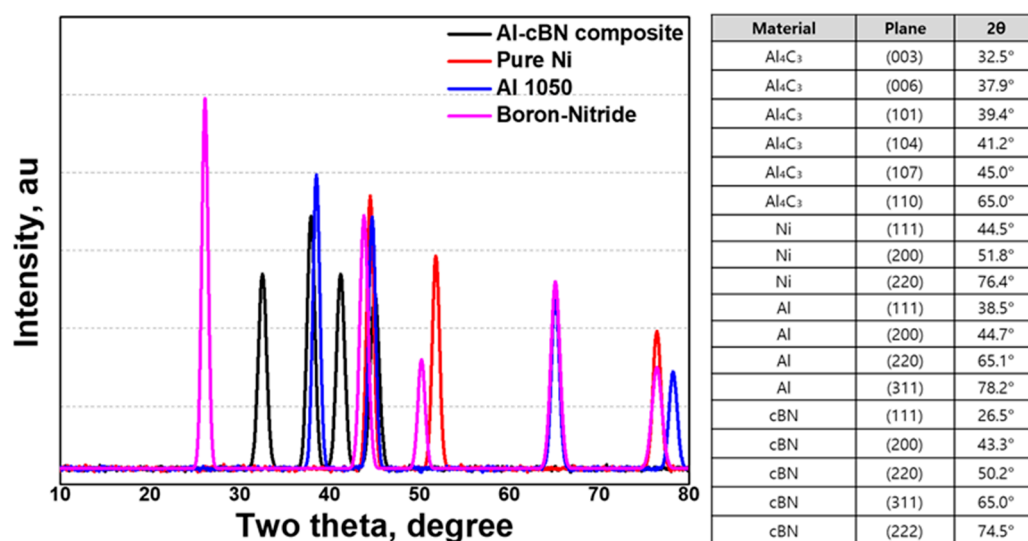


Figure 3. Representative XRD patterns of cBN, Al, and Ni phases for crystallographic phase identification and comparative analysis of the Al–cBN composite system.

In the 38–45° diffraction region, partial peak overlap behavior between the Al and Ni phases was observed due to the similar diffraction positions of Al (200) and Ni (111). Such overlap behavior may increase the difficulty of precise phase identification and crystallographic interpretation within the composite system. Furthermore, slight peak broadening and intensity variation were observed, indicating localized structural heterogeneity and interfacial interactions among the Al matrix, Ni phase, and cBN reinforcement particles. These results suggest that microstructural evolution near the interfacial regions plays an important role in determining the structural stability and electrochemical behavior of the Al–cBN composite system [25,37].

3.2. Surface Condition After Ni Plating

The characteristics of electroless Ni plating are strongly influenced by plating time, and the resulting coating behavior varies depending on the substrate condition and interfacial characteristics. Figure 4 presents the FE-SEM images of the Al–cBN composite surface as a function of plating time. In the uncoated specimen shown in Figure 4a at 0 s, a relatively heterogeneous surface morphology was observed. The surface consisted of the Al matrix together with dispersed cBN reinforcement regions distributed throughout the composite structure. In addition, fine granular features and irregular contrast differences were clearly observed, which are attributed to the different microstructural characteristics and compositional contrast between the Al matrix and cBN reinforcement regions. Such

heterogeneous microstructures can act as preferential nucleation sites during the subsequent electroless Ni deposition process.

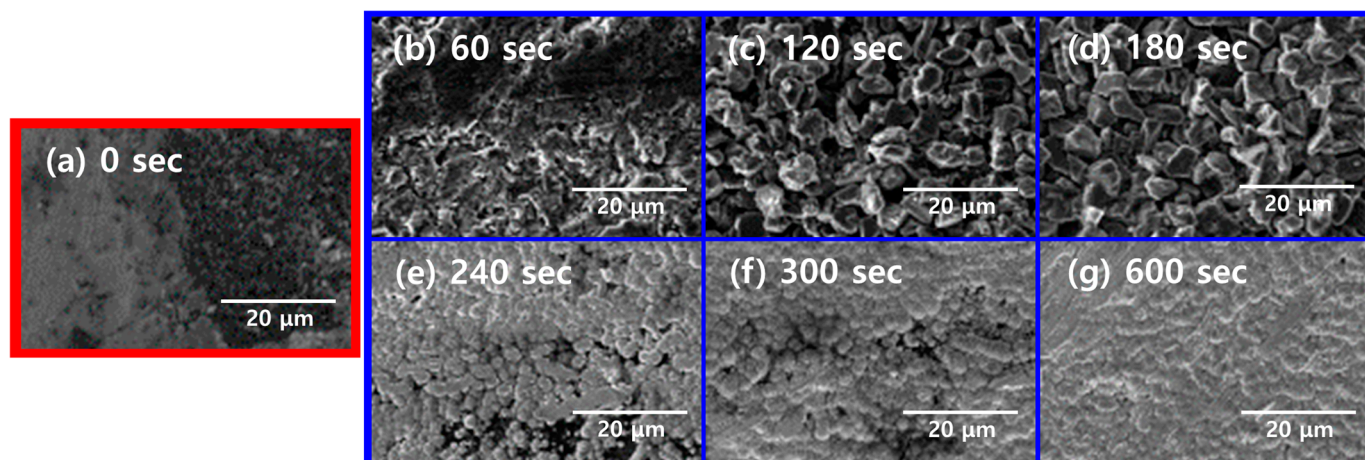


Figure 4. FE-SEM surface morphologies of the Al–Ni–cBN composite under different electroless Ni plating times: (a) 0 s, (b) 60 s, (c) 120 s, (d) 180 s, (e) 240 s, (f) 300 s, and (g) 600 s.

As the plating time increased, significant microstructural evolution of the Ni coating layer was observed. In Figure 4b,c, corresponding to 60 s and 120 s plating conditions, fine Ni particles began to nucleate on the composite surface. At this stage, localized nodular nuclei formation and isolated particle growth behavior were observed, indicating that the initial Ni deposition proceeded through discrete nucleation sites rather than continuous film formation. Furthermore, exposed substrate regions and localized microstructural discontinuities were still observed, suggesting that the coating layer remained non-uniform during the early deposition stage. At 180 s, however, both the size and density of the Ni particles increased significantly, and most of the surface became covered by the growing coating layer. This result indicates that the coating process transitioned from a nucleation-dominant stage to an active grain growth stage accompanied by rapid surface coverage [18,22].

Further increases in plating time resulted in the formation of a denser and more continuous coating structure. In the 240 s and 300 s specimens shown in Figure 4e,f, strong interparticle bonding and particle coalescence were observed, leading to the development of a compact coating layer. The initially isolated Ni particles gradually interconnected to form a continuous surface structure, while the density of surface pores and localized defects noticeably decreased. In the specimen plated for 600 s shown in Figure 4g, a relatively uniform and dense surface morphology was achieved. Compared with the initial Al–cBN composite surface, both surface roughness and localized defects were significantly reduced. These results demonstrate that increasing plating time promotes the growth and surface coverage of the Ni coating layer, thereby improving coating compactness and structural uniformity. Consequently, prolonged plating conditions can provide a more stable protective layer capable of enhancing the surface stability and corrosion resistance of the Al–cBN composite system.

Figure 5 presents the XRD pattern evolution of the Al–cBN composites according to electroless Ni plating time. In the initial Al–cBN composite, characteristic FCC diffraction peaks corresponding to Al (111), Al (200), Al (220), and Al (311) were observed together with representative diffraction peaks (black arrows in Figure 5) of the cBN reinforcement phase. The diffraction peaks corresponding to the cBN phase confirmed the successful incorporation and distribution of the reinforcement particles within the composite structure. In addition, slight peak overlap behavior was observed within the 38–45° diffraction region due to the similar diffraction positions of the Al and Ni phases. These results

indicate that multiple crystalline phases coexisted within the composite system prior to Ni plating [13,16].

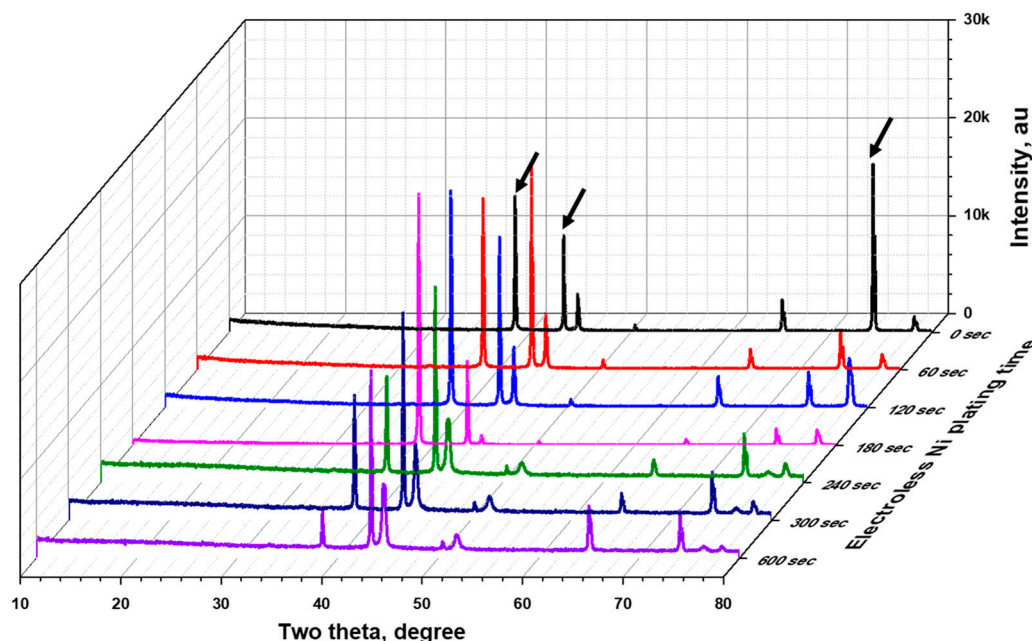


Figure 5. XRD patterns of the electroless Ni-plated cast Al-cBN composites under different plating times from 0 s to 600 s.

As the Ni plating time increased, distinct crystallographic changes associated with the formation and growth of the Ni coating layer were observed. In particular, the diffraction peak intensities corresponding to Ni (111), Ni (200), and Ni (220) near 44.5° , 51.8° , and 76.4° gradually increased with increasing plating time. This result indicates that both the growth and crystallinity of the Ni coating layer improved as the plating process proceeded. In contrast, the diffraction intensities associated with the Al matrix and cBN reinforcement gradually decreased due to progressive surface coverage by the growing Ni coating layer. Furthermore, under prolonged plating conditions, the Ni diffraction peaks became sharper and more intense, indicating the formation of a denser and more stable coating structure with enhanced crystallographic ordering. These results demonstrate that electroless Ni plating effectively promotes the formation of a protective surface layer on the Al-Ni-cBN composite [17,19].

A pronounced increase in diffraction peak intensity was observed for the specimen plated for 180 s. This behavior can be interpreted in terms of the evolution of the Ni coating layer from discontinuous nuclei to a more coherent and continuous crystalline film. In the early stages of electrodeposition, namely at 60 and 120 s, Ni deposition was governed primarily by heterogeneous nucleation on the Al-cBN composite surface. At this stage, the limited surface coverage and the presence of small crystalline domains resulted in relatively weak and broadened Ni diffraction peaks.

With increasing plating time to 180 s, the initially isolated Ni nuclei progressively coalesced, leading to the formation of a continuous Ni coating layer with improved crystallographic coherence. The increased continuity of the coating layer is expected to increase the effective diffracting volume of the Ni phase, thereby enhancing the overall diffraction intensity. In particular, the marked increase in the Ni (111) peak intensity suggests that the crystallographic growth of the Ni coating may have occurred preferentially along the close-packed (111) plane, which is commonly associated with a relatively low surface energy configuration in face-centered cubic Ni.

Compared with the 120 s condition, the Ni diffraction peaks at 180 s became sharper and more intense, indicating enhanced crystallinity and coating continuity. Furthermore, after 180 s, the diffraction peak intensities continued to increase gradually with increasing plating time (240–600 s), while no abrupt changes in peak position were observed. This behavior suggests that the coating growth mechanism transitioned from isolated nucleation and particle coalescence to continuous layer thickening and densification. The progressive increase in peak intensity after 180 s is consistent with the FE-SEM observations, which revealed increased surface coverage, particle interconnection, and the formation of a dense and uniform Ni coating layer. These results suggest that the 180 s plating condition represents a critical transition stage from discrete nucleation behavior to continuous crystallographic growth of the Ni coating layer.

Glow discharge spectroscopy (GDS) is an effective analytical technique for evaluating coating layers because it enables compositional analysis as a function of depth. The GDS results of the electroless Ni-plated Al–cBN composites at different plating times are presented in Figure 6 and summarized in Table 2. In the uncoated specimen (0 s), no Ni signal was detected, while the Al signal was dominant throughout the entire depth range, indicating direct exposure of the Al substrate. In addition, B and N signals were detected, confirming the presence of cBN reinforcement particles within the composite. In contrast, specimens subjected to electroless Ni plating exhibited a strong Ni signal in the surface region, and the depth over which the Ni signal was maintained gradually increased with increasing plating time. Specifically, Ni coating layers with thicknesses of approximately 0.2, 0.5, and 0.8 μm were formed under plating times of 60, 120, and 180 s, respectively, whereas the coating thickness further increased to approximately 1.2 and 1.8 μm under 240 and 300 s conditions. Furthermore, a gradual decrease in Ni concentration accompanied by an increase in Al concentration was observed in the interfacial region, indicating the formation of a distinct compositional gradient between the Ni coating layer and the Al substrate.

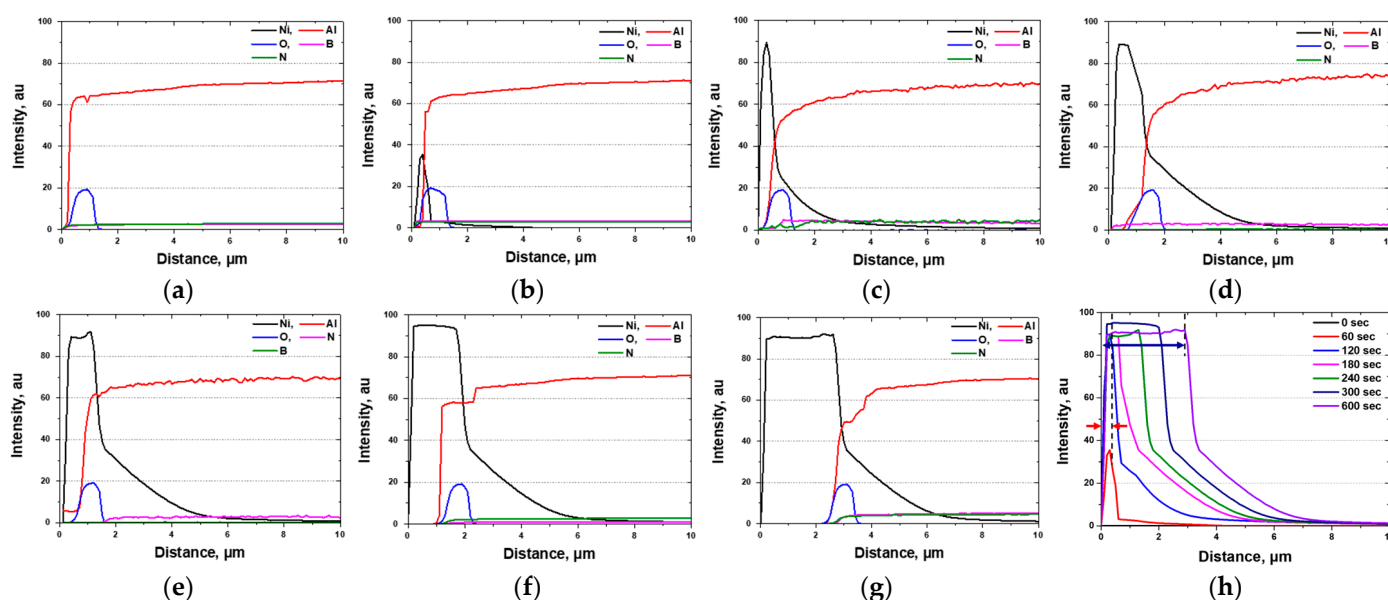


Figure 6. GDS results of the electroless Ni-plated cast Al–cBN composites under different plating times from 0 s to 600 s: (a) 0 s (Before Ni plating), (b) 60 s, (c) 120 s, (d) 180 s, (e) 240 s, (f) 300 s, (g) 600 s, and (h) Ag layer comparison.

Table 2. Major values of GDS results of the electroless Ni-plated cast Al–cBN composites under different plating times from 0 s to 600.

Ni Plating Time	0 s	60 s	120 s	180 s	240 s	300 s	600 s
Depth of Ni layer, μm	0 ± 0.00	0.2 ± 0.2	0.5 ± 0.4	0.8 ± 0.5	1.2 ± 0.4	1.8 ± 0.4	2.3 ± 0.1

Under the 600 s plating condition, the Ni coating layer reached a thickness of approximately 2.3 μm , exhibiting the widest Ni distribution region among all specimens. However, despite the plating time being doubled from 300 to 600 s, the increase in coating thickness was relatively limited. This behavior is attributed to the transition of the growth mechanism from rapid nucleation and surface coverage during the initial deposition stage to particle coalescence and coating densification after most of the substrate surface had already been covered by Ni. This interpretation is consistent with the FE-SEM observations, which revealed the formation of a continuous Ni layer and progressive surface smoothing with increasing plating time. In addition, the decrease in the surface Al signal and the dominance of the Ni signal indicate that the Ni coating layer effectively suppressed direct contact between the electrolyte and the Al substrate. Therefore, prolonged electroless Ni plating not only increases coating thickness but also enhances coating uniformity and compactness, thereby contributing to improved electrochemical stability and corrosion resistance of the Al–cBN composite system.

The thickness of the plated layer can be directly checked through cross-sectional observations. Figure 7 shows the cross-sectional SEM images of the Al–cBN composites and the corresponding thickness variation of the Ni coating layer as a function of plating time. For the uncoated specimen at 0 s, no distinct coating layer was observed on the composite surface, and the surface exhibited a rough morphology associated with the heterogeneous microstructure of the Al–cBN composite. After Ni plating for 60 s, fine Ni nuclei were discontinuously formed on localized regions of the surface, indicating that heterogeneous nucleation was dominant during the initial stage of deposition. As the plating time increased to 120 s, the Ni deposits became progressively connected; however, the coating layer remained thin and partially nonuniform. At the plating time of 180 s, a continuous Ni coating layer was clearly observed on the surface of the Al–cBN composite. This result suggests that the individually formed Ni nuclei coalesced and grew, leading to the formation of a more compact coating layer. With further increases in plating time to 240 and 300 s, the thickness of the Ni coating layer increased, and the coating exhibited a more uniform and dense cross-sectional structure. After 600 s of plating, the Ni coating layer was formed, showing a relatively flat and compact cross-sectional morphology.

The thickness analysis shown in Figure 7h also confirms that the Ni coating thickness gradually increased with increasing plating time. The Ni coating thickness was nearly 0 μm for the uncoated specimen and increased to 0.2 μm and 0.3 μm after 60 and 120 s of plating, respectively. The thickness then increased more distinctly to 0.8 μm at 180 s, followed by 1.2 μm and 1.8 μm at 240 and 300 s, respectively. The Ni coating thickness reached 2.3 μm after 600 s of plating. These results indicate that Ni deposition initially proceeded through nucleation and discontinuous particle growth, whereas a continuous coating layer formed after a sufficient plating duration, resulting in a more pronounced increase in thickness. Therefore, the cross-sectional SEM observations and thickness measurements demonstrate that increasing the plating time effectively improves the continuity, compactness, and thickness of the Ni coating layer on the Al–cBN composite.

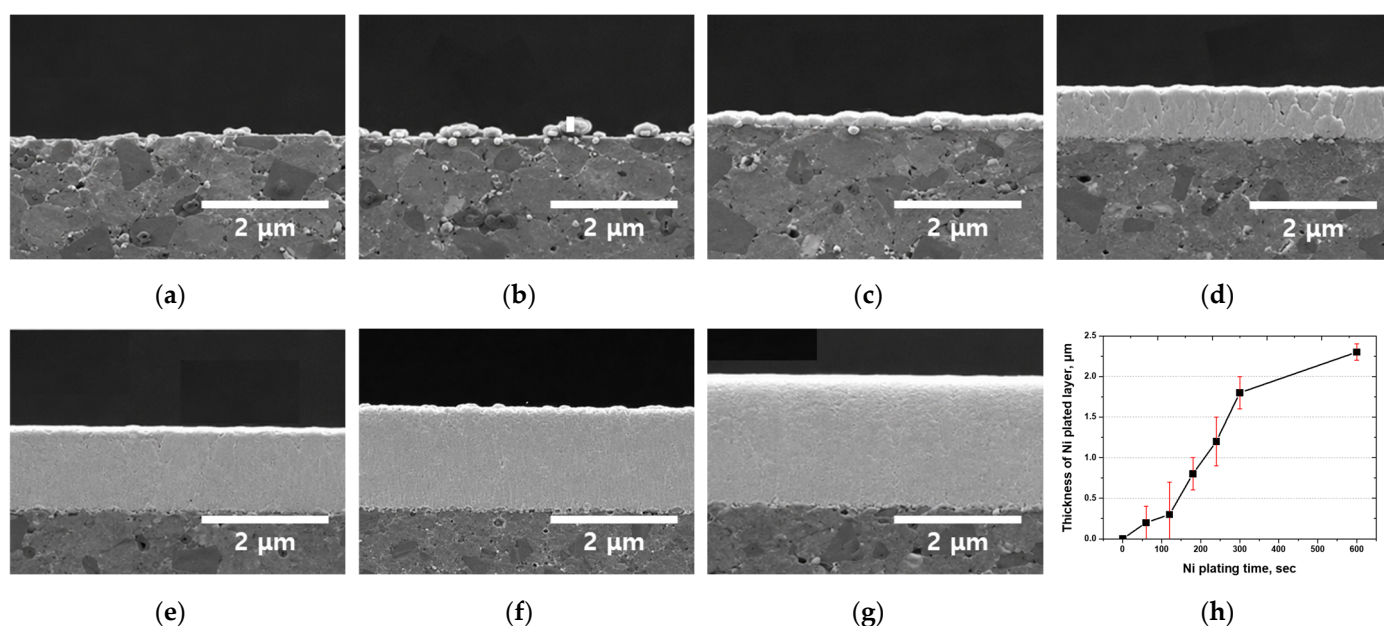


Figure 7. Cross-section images of the electroless Ni-plated cast Al-cBN composites under different plating times from 0 s to 600 s: (a) 0 s (before Ni plating), (b) 60 s, (c) 120 s, (d) 180 s, (e) 240 s, (f) 300 s, (g) 600 s, and (h) Ni plating time (s) vs. Ni thickness (μm).

3.3. Electrochemical Behavior

The electrochemical reactivity of metallic materials can be estimated based on the EMF series; however, the actual electrochemical response is strongly influenced by surface condition, microstructural heterogeneity, and environmental parameters [29,38]. Furthermore, the electrochemical potential of alloys and composite systems cannot be directly determined from the EMF series because of the coexistence of multiple phases and interfacial interactions. Therefore, OCP measurements were employed to evaluate the relative electrochemical stability of the fabricated specimens. Figure 8 and Table 3 present the OCP behavior of pure Al, cBN, Al-cBN composites, and electroless Ni-plated Al-cBN composites. Pure Al exhibited relatively negative potential values, which are associated with the highly active anodic characteristics of Al and its susceptibility to anodic dissolution in chloride-containing electrolytes. In contrast, cBN exhibited relatively stable electrochemical behavior due to its chemically stable ceramic characteristics. The Al-cBN composite showed a relatively unstable potential region compared with pure Al, indicating increased electrochemical heterogeneity caused by the coexistence of multiple phases and interfacial regions within the composite structure.

Table 3. Representative open circuit potential (OCP) values measured in 3.5 wt.% NaCl solution for (a) Al 1050, cBN, Al-cBN composite, and pure Ni specimens, and (b) electroless Ni-plated Al-cBN composites at different plating times.

(a)	Al1050		cBN		Al-cBN		Pure Ni
Potential, V	-0.86 ± 0.05		-0.05 ± 0.02		-1.09 ± 0.05		-0.29 ± 0.02
(b)	0 s	60 s	120 s	180 s	240 s	300 s	600 s
Potential, V	-1.08 ± 0.12	-1.12 ± 0.10	-1.20 ± 0.12	-1.25 ± 0.11	-1.33 ± 0.13	-1.35 ± 0.14	-0.39 ± 0.2

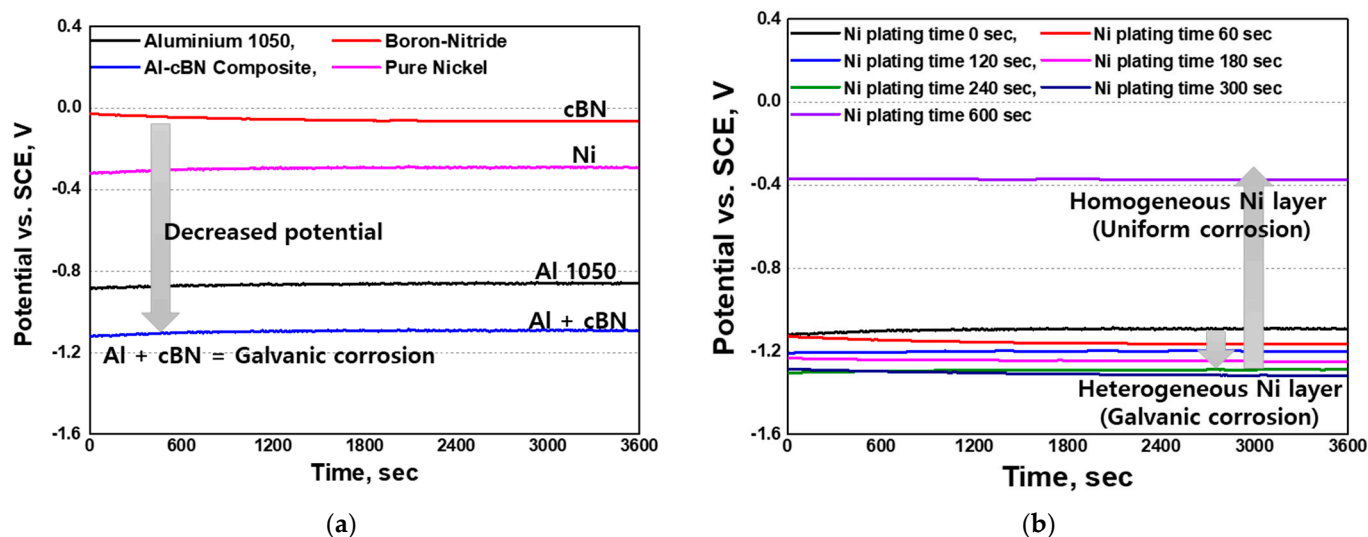


Figure 8. Open circuit potential (OCP) curves measured in 3.5 wt.% NaCl solution: (a) comparison of pure Al, cBN, Al-cBN composite, and pure Ni specimens, and (b) OCP behavior of electroless Ni-plated Al-cBN composites under different plating times.

The Al-cBN composite exhibited pronounced potential fluctuations during immersion, suggesting the occurrence of localized electrochemical instability near the interfacial regions between the Al matrix and cBN reinforcement. The heterogeneous microstructure and localized surface discontinuities promoted non-uniform electrochemical activity within the composite system. Furthermore, interfacial defects and localized surface heterogeneity contributed to unstable passive film formation and localized electrochemical reactions during immersion in the chloride-containing electrolyte. These results indicate that the heterogeneous interfacial structure of the Al-cBN composite can accelerate localized electrochemical degradation and reduce electrochemical stability.

Following electroless Ni plating, the OCP values shifted toward a more noble potential region, indicating enhanced electrochemical stability of the composite surface. This behavior is attributed to the formation of a dense Ni coating layer that effectively suppressed direct electrochemical interaction between the electrolyte and the Al substrate. Furthermore, the Ni coating layer reduced interfacial electrochemical reactions and functioned as a protective barrier layer, thereby improving passive film stability on the composite surface. As the plating time increased, the OCP values progressively shifted toward more noble potentials, indicating enhanced coating compactness and increased surface coverage. Consequently, electroless Ni plating effectively improved the electrochemical stability and corrosion resistance of the Al-cBN composite through surface modification.

Potentiodynamic polarization analysis was performed to evaluate the electrochemical corrosion behavior of the fabricated specimens by measuring the current density response as a function of applied potential [39,40]. Figure 9a and Table 4a present the potentiodynamic polarization behavior of Al 1050, cBN, Al-cBN composites, and pure Ni. Al 1050 exhibited a rapid increase in anodic current density within the low potential region, indicating active anodic dissolution behavior in the chloride-containing electrolyte. In contrast, cBN exhibited relatively stable electrochemical behavior with a low current response due to its chemically stable ceramic characteristics. The Al-cBN composite exhibited a more negative corrosion potential (E_{corr}) and higher anodic current density compared with pure Al, indicating reduced electrochemical stability and accelerated corrosion activity within the composite system. This behavior is attributed to localized electrochemical heterogeneity and interfacial instability caused by the coexistence of multiple phases within the composite structure. Furthermore, localized surface discontinuities and hetero-

geneous interfacial regions promoted non-uniform anodic dissolution behavior during electrochemical polarization.

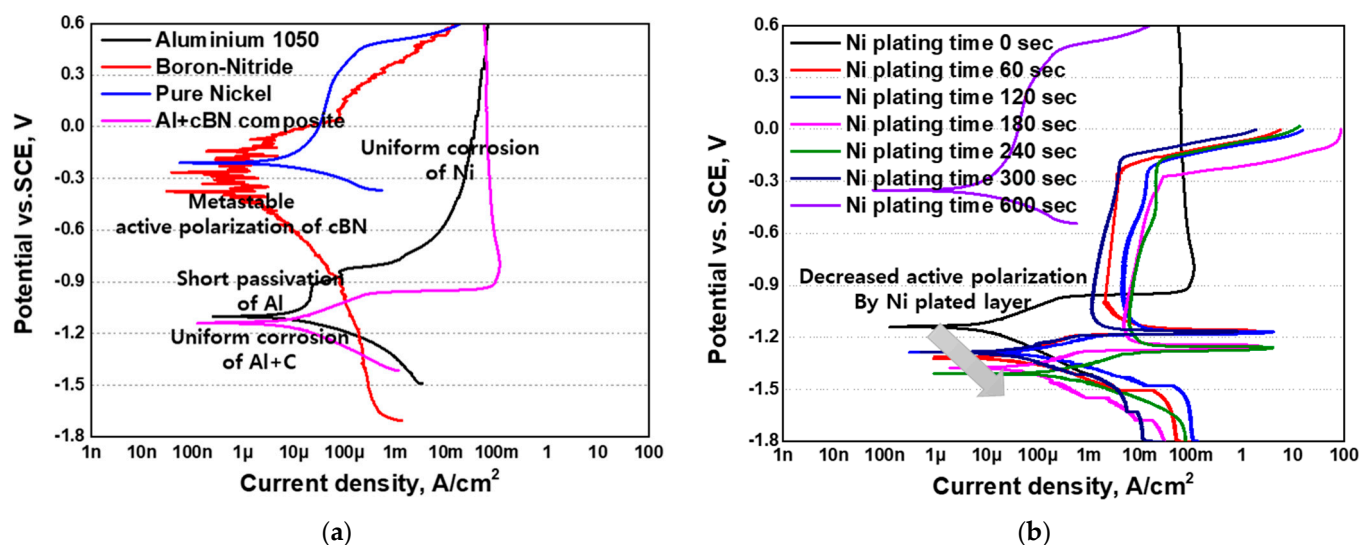


Figure 9. Potentiodynamic polarization curves measured in 3.5 wt.% NaCl solution: (a) comparison of Al 1050, cBN, Al-cBN composite, and pure Ni specimens, and (b) polarization behavior of electroless Ni-plated Al-cBN composites under different plating times.

Table 4. Representative E_{corr} and I_{corr} values at active polarization on the potentiodynamic polarization test measured in 3.5 wt.% NaCl solution for (a) Al 1050, cBN, Al-cBN composite, and pure Ni specimens, and (b) electroless Ni-plated Al-cBN composites at different plating times.

(a)	Al1050		cBN		Al-cBN		Pure Ni
$E_{\text{corr}}, \text{V}$	-1.06 ± 0.05		-0.27 ± 0.03		-1.12 ± 0.11		-0.20 ± 0.02
$I_{\text{corr}}, \text{A}/\text{cm}^2$	$1 \times 10^{-5} \pm 2 \times 10^{-4}$		$9 \times 10^{-6} \pm 3 \times 10^{-4}$		$1 \times 10^{-5} \pm 3 \times 10^{-4}$		$8 \times 10^{-6} \pm 3 \times 10^{-5}$
(b)	0 s	60 s	120 s	180 s	240 s	300 s	600 s
$E_{\text{corr}}, \text{V}$	-1.12 ± 0.11	-1.30 ± 0.20	-1.30 ± 0.22	-1.36 ± 0.24	-1.39 ± 0.26	-1.25 ± 0.29	-0.32 ± 0.03
$I_{\text{corr}}, \text{A}/\text{cm}^2$	$1 \times 10^{-5} \pm 3 \times 10^{-4}$	$1 \times 10^{-4} \pm 1 \times 10^{-3}$	$1 \times 10^{-4} \pm 1 \times 10^{-3}$	$1 \times 10^{-4} \pm 1 \times 10^{-3}$	$2 \times 10^{-4} \pm 2 \times 10^{-3}$	$3 \times 10^{-4} \pm 2 \times 10^{-3}$	$3 \times 10^{-5} \pm 2 \times 10^{-4}$

Figure 9b and Table 4b present the polarization behavior of the Al-cBN composites as a function of electroless Ni plating time. Following electroless Ni plating, the corrosion potential shifted toward a more noble region, while the overall anodic current density decreased significantly compared with the uncoated Al-cBN composite. As the plating time increased, a more distinct passivation region was observed, indicating the formation of a stable electrochemical barrier layer on the composite surface. This behavior is attributed to the Ni coating layer effectively suppressing direct electrochemical interaction between the electrolyte and the Al substrate while reducing interfacial electrochemical reactions. During the initial plating stage, localized current fluctuations were observed due to coating non-uniformity and incomplete surface coverage (Gray allow in Figure 9b). However, as the plating time increased to 600 s, the polarization behavior gradually approached that of pure Ni, indicating the formation of a dense and continuous Ni coating layer with enhanced electrochemical stability [41,42].

Under prolonged Ni plating conditions, the corrosion current density (I_{corr}) decreased markedly, while the anodic branch exhibited a reduced slope, indicating suppression of anodic dissolution kinetics [43,44]. These results demonstrate that the Ni coating layer functioned as an effective electrochemical barrier layer that inhibited electrolyte penetration

and localized corrosion propagation. In addition, several specimens exhibited localized current fluctuations associated with passive film breakdown and metastable pitting behavior [45,46]. Nevertheless, the overall electrochemical stability of the Al–cBN composite was significantly improved after electroless Ni plating [47,48]. However, non-uniform Ni coating regions may generate localized electrochemical activity because of potential differences between exposed Al-based regions and the Ni coating layer. Therefore, coating uniformity and surface coverage are critical factors governing the corrosion resistance and long-term electrochemical stability of electroless Ni-plated Al–cBN composites.

4. Discussion

Al–cBN composites are recognized as lightweight structural materials capable of simultaneously achieving enhanced mechanical performance and reduced density through the incorporation of ceramic reinforcement phases into the Al matrix [11,12]. In the present study, Al–cBN composites were fabricated using an Al 1050 matrix reinforced with cBN particles. The incorporation of cBN reinforcement generated heterogeneous interfacial regions within the composite structure, which can contribute to improved mechanical stability and load transfer behavior. However, the coexistence of multiple phases and interfacial heterogeneity may reduce electrochemical stability under humid and chloride-containing environments by promoting localized electrochemical activity and non-uniform anodic dissolution behavior. These characteristics can accelerate localized corrosion and reduce the long-term corrosion resistance of the composite system [49,50].

To further illustrate the evolution mechanism of the electroless Ni coating layer, a schematic diagram based on the FE-SEM observations is presented in Figure 10. During the initial plating stage (0–120 s), localized Ni nuclei were heterogeneously formed on the Al–cBN composite surface, resulting in isolated particle growth and incomplete surface coverage. At approximately 180 s, rapid particle growth and interparticle connectivity were observed, indicating a transition from the nucleation-dominant stage to the active coating growth stage. With further increases in plating time (240–600 s), particle coalescence and layer densification progressively occurred, leading to the formation of a dense, continuous, and uniform Ni coating layer. These results suggest that prolonged electroless Ni plating promotes coating compactness, surface coverage, and structural uniformity, thereby enhancing the surface stability and corrosion resistance of the Al–cBN composite system [13,16].

XRD analysis demonstrated that the diffraction peak intensities corresponding to Ni (111), Ni (200), and Ni (220) progressively increased with increasing plating time. In contrast, the diffraction intensities associated with the Al matrix and cBN reinforcement gradually decreased because of the progressive surface coverage of the substrate by the growing Ni coating layer [13,16]. Furthermore, overlapping diffraction behavior between Al and Ni phases was observed within the 38–45° diffraction region. A significant increase in diffraction peak intensity was particularly observed under the 180 s condition, which is attributed to rapid grain growth and preferred orientation development during coating layer evolution. These results indicate that the crystallographic growth behavior of the Ni coating layer strongly depended on plating time and coating continuity.

The growth behavior of the electroless Ni coating layer can be explained by the autocatalytic deposition mechanism of electroless plating [19,21]. During the initial plating stage, the Al–cBN composite surface contained heterogeneous active sites associated with the Al matrix and cBN reinforcement regions. These microstructural heterogeneities promoted localized Ni nucleation rather than uniform surface deposition. Consequently, isolated Ni particles were initially formed on the composite surface, resulting in discontinuous coating coverage. As the plating process proceeded, the deposited Ni particles acted as catalytic

sites for further Ni reduction, accelerating particle growth and interparticle coalescence. Therefore, the coating evolution mechanism gradually transitioned from isolated nucleation to continuous layer formation and densification. The significant increase in coating continuity observed after 180 s suggests that a critical surface coverage threshold was reached, enabling rapid lateral growth and the formation of a continuous protective layer.

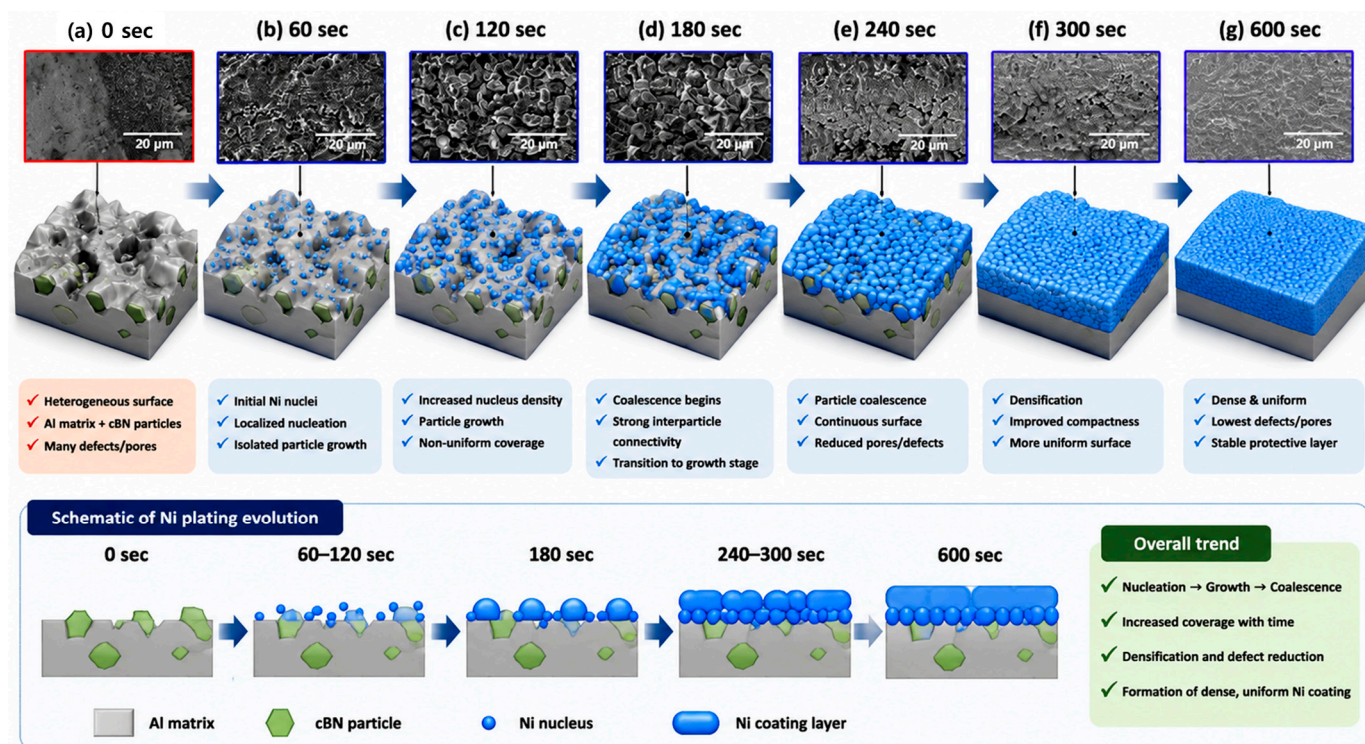


Figure 10. Schematic illustration of the electroless Ni coating evolution mechanism on the Al–cBN composite surface according to plating time.

OCP analysis revealed that the Al–cBN composite exhibited a more negative potential region than Al 1050, indicating reduced electrochemical stability and increased anodic dissolution behavior caused by localized electrochemical heterogeneity within the composite structure. In contrast, the Ni-coated specimens exhibited a shift toward more noble potentials, while potential fluctuations gradually decreased with increasing plating time. This behavior is attributed to the suppression of interfacial electrochemical reactions resulting from the formation of a dense Ni coating layer that effectively blocked direct electrolyte contact with the Al substrate. Potentiodynamic polarization analysis further demonstrated that electroless Ni plating significantly reduced the corrosion current density and promoted the formation of a distinct passivation region.

Under prolonged plating conditions, the polarization behavior gradually approached that of pure Ni, indicating that most of the composite surface was covered by a continuous and dense Ni coating layer. However, localized electrochemical activity was still observed under the initial plating conditions because of coating non-uniformity and incomplete surface coverage. Therefore, electroless Ni plating is considered an effective surface modification technique for improving the electrochemical stability and corrosion resistance of Al–cBN composites, although optimization of coating uniformity and coating compactness remains essential for achieving long-term corrosion protection.

Based on these results, galvanic corrosion behavior should be considered when evaluating the corrosion resistance of electroless Ni-plated Al–cBN composites [51,52]. Owing to the significant electrochemical potential difference between the Ni coating layer and the Al

substrate, localized galvanic cells can form in regions where the coating is non-uniform or where portions of the Al–cBN substrate remain exposed. In such cases, the exposed Al matrix acts as the anodic region and preferentially undergoes dissolution, whereas the Ni-coated regions function as cathodic sites. Consequently, localized corrosion can be accelerated at coating defects, pores, or incompletely covered regions. This phenomenon is particularly significant during the early plating stages (60–180 s), where discontinuous Ni coverage and isolated coating islands were observed in the FE-SEM images. As the plating time increased, the formation of a dense and continuous Ni coating layer reduced the exposed substrate area and minimized the galvanic coupling effect between the Ni coating and the Al–cBN substrate. Therefore, the corrosion protection mechanism of electroless Ni plating is governed not only by the barrier effect of the coating layer but also by the suppression of localized galvanic corrosion through improved coating continuity and surface coverage.

5. Conclusions

Ni plating was successfully applied to Al–cBN composites, and the following conclusions were obtained:

- (1) The fabricated Al–cBN composite exhibited heterogeneous microstructures consisting of the Al matrix and dispersed cBN reinforcement phases. FE-SEM and XRD analyses confirmed the coexistence of multiple phases and heterogeneous interfacial regions within the composite system. The heterogeneous microstructure increased localized electrochemical activity and reduced electrochemical stability because of non-uniform interfacial characteristics within the composite structure. EDS analysis revealed that the cBN-rich regions contained 11 wt.% reinforcement content, indicating successful incorporation of the reinforcement phase within the Al matrix.
- (2) The growth behavior of the electroless Ni coating layer strongly depended on plating time. During the initial plating stage, localized Ni nuclei formed heterogeneously on the composite surface, while prolonged plating promoted particle coalescence and continuous coating layer formation. Under the 600 s plating condition, a dense and uniform coating layer was successfully formed. XRD analysis revealed that the diffraction peak intensities corresponding to Ni (111), Ni (200), and Ni (220) progressively increased with increasing plating time, indicating enhanced crystallinity and preferred orientation development within the coating layer. GDS analysis showed that the Ni coating thickness increased from approximately 0.2 μm at 60 s to 2.3 μm at 600 s, demonstrating progressive coating growth and surface coverage with increasing plating time.
- (3) Electrochemical analysis demonstrated that the Al–cBN composite exhibited lower electrochemical stability and higher corrosion activity than pure Al because of localized electrochemical heterogeneity and interfacial instability within the composite structure (OCP: $-1.08 \sim -1.10$ V; E_{corr} : -1.12 V; I_{corr} : 1×10^{-5} A/cm²). After electroless Ni plating, the OCP shifted toward a more noble potential region (from -1.08 V at 0 s to -0.39 V at 600 s), while the corrosion current density decreased (from -1.12 V to -0.32 V). In addition, a more stable passivation region was observed in the potentiodynamic polarization curves as plating time increased. These results indicate that the Ni coating layer effectively suppressed anodic dissolution and improved the electrochemical stability of the Al–cBN composite by functioning as a protective barrier layer. However, localized electrochemical activity was still observed under non-uniform coating conditions, indicating that coating uniformity and compactness are critical factors governing long-term corrosion resistance.

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