

Article

Concentration Influence of Complexing Agent on Electrodeposited Zn-Ni Alloy

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Abstract: Zinc (Zn) coatings, which are widely used to protect metals from corrosion, can be further improved by alloying with nickel (Ni). Increasing the Ni content enhances the corrosion-resistant properties of the Zn coating. This study investigated the effect of tetraethylenepentamine (TEPA) concentration on the Ni content and the properties of the Zn-Ni alloy coating. Zn-Ni alloy coatings were electrodeposited via the Hull cell test with TEPA concentrations of 0, 0.035, 0.07, and 0.1 M. We found that increasing the TEPA concentration improved the brightness of the coating at low current density and influenced the crystal orientation and morphology. When the TEPA concentration was increased to 0.7 M, the Ni content of the Zn-Ni alloy coating significantly increased before leveling off. However, the thickness of the coatings decreased with increasing TEPA concentration. The electrochemical behavior of the Zn-Ni alloy electrodeposition was validated via partial polarization curves of the Zn and Ni depositions.

Keywords: Zn-Ni alloy; electrodeposition; complexing agent; Ni content; gloss



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1. Introduction

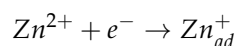
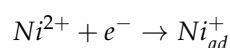
Steels are the most common materials used in diverse industries, such as construction, automotive, energy, and aerospace. To meet application requirements, they are tough and durable with high yield and ultimate tensile strengths. While operating, steels are subjected to corrosive environments, such as an aqueous solution, leading to an initial stress corrosion crack. Unfortunately, the corrosion-resistant property of steel is too low. Therefore, a sacrificial protective coating is essential to prolong the life expectancy of steel.

Zinc (Zn) electroplating, also known as galvanizing, is the most widely used metal coating. Electroplated binary Zn-X alloys, in which X is an iron group metallic element (Fe, Co, or Ni), possess enhanced properties, especially corrosion resistance, compared to pure Zn [1–5]. Zn alloys have been used as a sacrificial coating to protect stainless steel, as their reduction potential is lower than that of stainless steel. Due to the low reduction potential, these alloys corrode more preferentially than steels, thereby increasing the lifetime of materials. Owing to its excellent corrosion-resistant properties, Zn-Ni alloy coating has generated considerable interest recently [6–10].

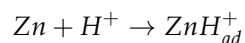
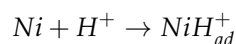
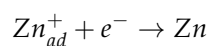
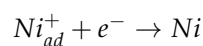
Electrodeposition is an electrochemical method highly preferable for preparing coating due to its unique ease of controlling the thickness and chemical composition of the coatings via the deposition conditions, such as current density, pH, and composition bath. In this technique, the deposition of coating is carried out onto a cathodic substrate by the reduction of metallic cations. Conventional electrodeposition of Zn-Ni alloy is conducted in aqueous solutions, and Zn-Ni alloy coatings can be obtained from sulfate, chloride, acid, weak acid, and alkaline bath solutions [11–14]. Weak acid baths usually operate at high current densities, yielding Zn-Ni alloy coatings with a relatively low Ni content and non-uniform distribution of Ni element throughout the deposit. Conversely, alkaline electrolytes operate

at low current density and provide uniform Ni distribution with a higher content than that produced by acid baths. Alkaline solutions, including cyanide and zincate, yield higher throwing power than their counterparts [15–17]. While cyanide solution shows high toxicity in the environment, zincate is an eco-friendly candidate. Moreover, zincate solution has some advantages such as low hydrogen embrittlement and uniform plating layers. Additionally, the bath solution is less corrosive to equipment, affordable, and easy to control. The typical composition of zincate solution consists of Zn and Ni ion compounds, such as ZnO, and $\text{Ni}_2\text{SO}_4 \cdot 6\text{H}_2\text{O}$, sodium hydroxide (NaOH), and organic additives [18]. The addition of additives in electroplating is essential as they impact the growth and structure of the deposits, thereby enhancing the appearance and properties of coatings or the performance of the bath.

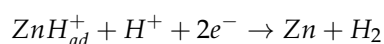
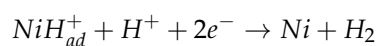
Hydrogen generation evolution reaction (HER) during Zn and Zn alloy electrodeposition may cause hydrogen embrittlement. The existence of hydrogen traps may yield residual stresses, resulting in delayed failures of the electroplated coatings. Hydrogen generation can be specified according to the reduction that takes place at the cathode as follows. First, Ni^{+2} and Zn^{+2} ions are dissolved into adsorbed monovalent ions [19].



Subsequently, these adsorbed ions are reduced to metallic ions, which combines with hydrogen ion (H^+) to form NiH_{ad}^+ and ZnH_{ad}^+ .



Finally, these species are reduced to form metallic Zn and Ni, and to release H_2 .



Electroplated Zn-Ni alloys exist in three phases α , γ , and η [20]. Specifically, phase α is defined as a solid solution of Zn in Ni with the Zn amount smaller than 30%, possessing a face-centered cubic (FCC) structure. Phase η is a solid solution of Ni in Zn with a Ni amount smaller than 1%, possessing a hexagonal crystal structure. Phase γ is an intermetallic compound with a body-centered cubic (BCC) structure, containing the Ni amount from 10 to 30%. The phase γ of Zn-Ni alloy yields high corrosion resistance and good mechanical properties. Hence, electroplated phase γ is commonly applied as a corrosion protection layer for steels and metals [21]. Previous studies reported that the Zn-Ni alloy containing 12–18 wt.% of Ni content yielded 3–8-fold higher corrosion resistance than pure Zn coating [22]. This excellent property was attributable to the existence of the γ phase in the microstructure. The Zn-Ni alloy moreover exhibited a uniform and smooth surface without the degradation of strength, and ductility of steel. In addition, the phase composition can be determined by changing the variables of electrodeposition, such as the Ni/Zn ion ratio in bath solution, the current density, temperature, and stirring speed. One previous study proved that when the equilibrium potential of Zn was -1.00 , -0.94 , and -0.67 V versus a saturated calomel electrode (SCE), the η , γ , and α phases, respectively were deposited from a chloride electrolyte with Ni/Zn ion ratio of 5.0 [23].

To improve the corrosion resistance of Zn-Ni alloy coatings, an extrinsic factor can be added to the film. Notably, a chromate conversion coating is widely adopted as a corrosion

barrier. Different from $\text{Cr}_2\text{O}_7^{2-}$ or CrO_4^{2-} in hexavalent passivation, which preferentially tends to oxidize, the Cr^{3+} ion in trivalent passivation is stable with the lack of oxidation. The oxidizing incapability of Cr^{3+} creates a thinner passivation film than that of Cr^{6+} . The variables of chromate conversion coating, such as duration, temperature, and pH, directly affect the growth, bonding strength, and corrosion resistance of the passivation film. Our group reported adding a chromate coating as a post-treatment to increase the corrosion resistance of Zn-Ni coatings [24]. The combination of NaF additive concentration and eco-friendly trivalent chromate treatment time was investigated. When both the NaF concentration and chromate treatment time increased, the cracks on the chromate film reduced, suggesting that NaF accelerated the formation of chromate film. Meanwhile, the corrosion current decreased when the NaF concentration increased. Due to the presence of the chromate film, passivation was formed, suppressing the corrosion current, and improving the corrosion resistance.

In addition, high-corrosion-resistant Zn-Ni alloys also require intrinsic factors, i.e., a fine microstructure with either a high Zn content or a high Ni content. Particularly, a high Zn content, which is less noble than iron, should be obtained to use as a sacrificial film, or a high Ni content, which is nobler than iron, should be obtained to use as a barrier film. Previous research has mostly focused on factors that increase the Ni content since a higher amount of Ni leads to better corrosion resistance of coatings [25,26]. One effective approach is the addition of complexing agents in the plating solution [27,28]. The interaction between metallic ions and complexing agents that contain ions or functional groups can result in the formation of a complex. Hence, the complexing agent is expected to bind with Ni ions during electroplating, thereby reducing Ni hydroxide precipitation and improving Ni deposition efficiency. Feng et al. reported that the usage of complexing agent 5,5'-dimethylhydantoin induced strong adsorption on electrodes [29]. The deposition of Zn-Ni alloy was changed from normal to anomalous co-deposition with decreasing the applied deposition potential. Faïd et al. stated that the increase in the concentration of ethylenediaminetetraacetic acid (EDTA) yields more hydrogen evolution [30]. At low EDTA concentration, the refinement of microstructure could be obtained with low Zn content, the coating presented a γ -phase structure with better corrosion resistance. Muller et al. used various amines as complexing agents for Zn-Ni alloy electrodeposition [18]. Amines significantly affected the phase transformation of Zn-Ni alloy and crystal orientation. These complexing agents shifted the deposition potential more negatively and produced pore-free coatings.

In this study, we used tetraethylenepentamine (TEPA) as a complexing agent and investigated the effect of TEPA concentration on the electrodeposited Zn-Ni alloy coating. We examined the appearance of Zn-Ni coatings obtained by the Hull cell test with different TEPA concentrations via surface gloss. We also validated the microstructure relating to the variation in TEPA concentrations. Finally, we explored electroplating performance through thickness measurement, determination of Ni content, and partial polarization curves.

2. Materials and Methods

2.1. Hull Cell Experiment

A long Hull cell tank (LHC-4, Jungdo, Paju-si, Republic of Korea) with a volume of 500 mL was used for the experiment. A Ni anode (63(l) $\times$ 64(w) $\times$ 3(t) mm, Jungdo, Korea) was used, and a stainless-steel cathode for the long Hull cell (200(l) $\times$ 65(w) $\times$ 0.3(t) mm, Jungdo, Korea) was used as the cathode specimen. The solution composition comprised NaOH at 120 g/L, ZnO at 10 g/L, equivalent to 8 g/L of Zn^{2+} , Ni-CPL (i.e., NiSO_4 450 g/L) at 14 mL/L, equivalent to 1.4 g/L of Ni^{2+} , a brightener at 1 mL/L, and TEPA as a complexing agent. The concentration of TEPA varied at 0, 0.035, 0.7, and 1 M. A Hull cell test was conducted at 25 °C for 20 min with a current intensity of 2 A.

2.2. Electrochemical Analysis

The electrochemical analysis was conducted using the three-electrode method to validate the process of electrodeposition and to determine the influence of the complexing agent TEPA. Distilled water was adopted for the preparation of the electrolyte solution. A pure platinum (Pt) mesh electrode served as the counter electrode, and an Ag/AgCl/KCl electrode, which has a potential of 0.197 V versus a normal hydrogen electrode, was used as a reference electrode. An iron (Fe) cathode ($25 \times 40 \text{ mm}^2$) was used as the working electrode, and 500 mL of the electrolyte solution, which had a composition similar to the Hull cell test solution, was used for each analysis. Electrochemical polarization curves were obtained using a potentiostat/galvanostat (HA-151B, Hokuto Denko, Kanagawa, Japan). The Zn-Ni alloy plated from the electrochemical experiment was extracted using 50 vol% nitric acids. The resulting solution was quantitatively analyzed using an atomic absorption spectrometer (AAS, iCE 3000 Series, Thermo Fisher Scientific, Waltham, MA, USA) to determine the content of Zn and Ni elements.

2.3. Material Characterization

The thickness of the coatings obtained by the Hull cell test was measured at areas with different current densities using X-ray fluorescence spectroscopy (XRF, XAN 250, Helmut Fischer GMBH, Sindelfingen, Germany). The morphology of the Zn-Ni surface was investigated using a scanning electron microscope (SEM, PW-100-017, Phenom World, Eindhoven, The Netherlands). X-ray diffraction (XRD) was performed using an X-ray diffractometer (Empyrean, Malvern Panalytical, Almelo, The Netherlands) with $\text{CuK}\alpha$ radiation. 2 θ scans was between 20° and 90° . The external gloss of the coating layer was measured using a gloss meter (4563 (micro-TRI-gloss/ 20° , 60° , 85°), BYK Gardner, Wesel, Germany). The BYK Gardner micro-TRI-gloss gloss meter integrates 20° , 60° , and 85° measurements into one gloss meter to measure high, medium, and low gloss, with a measuring range from 0 to 2000 GU. The whiteness of the appearance of the coating layer was measured using a spectrophotometer (CM-2500d, Konica Minolta, Tokyo, Japan). The surface roughness of the plating layer's appearance was measured using a confocal laser scanning microscope (LSM700, Carl Zeiss, Göttingen, Germany).

3. Results and Discussion

3.1. Appearance of Zn-Ni Alloy Coating

The current density distribution over the cathodic area is usually a huge concern in electrodeposition. Thus, the Hull cell has been suggested to observe the variation in current density along the cathode. The Hull cell is defined as a miniature electroplating tank, in which a cathode is angled in respect of the anode; hence, the current density distribution is reversely proportional to the distance between the anode and the cathodic area. The appearance of Zn-Ni alloy coatings with different TEPA concentrations is shown in Figure 1a, in which the right direction is along with increasing current density, and the left direction is along with decreasing current density. TEPA concentration probably did not significantly affect the brightness of coatings in the high current area. However, increased TEPA concentration improved the coating brightness in the low current region. At TEPA 0 M, the dark area was dominant over half of the scanned area. When the TEPA concentration increased to 0.035 M, the dark area became smaller, and it disappeared when the TEPA concentration was over 0.07 M.

To further support this, the variation in glossiness according to the change of current density and TEPA concentration is represented in Figure 1b. The quality of the plating layer can be reflected by the plated surface gloss, which is higher when the mean grain size is smaller than the wavelength of visible light, i.e., smaller than $0.4 \mu\text{m}$ [31]. Additionally, the glossiness is significantly affected by the plating process. Thus, the change in TEPA concentration was expected to vary the surface gloss of the coating at different current densities. A similar trend to the appearance of coating could be observed according to the change in current density and TEPA concentration. Specifically, at low TEPA concentrations

of 0 M and 0.035 M, the gloss unit almost linearly increased with the decrease in current density before decreasing at a low current density of 2 A/dm² (ASD). The severe degradation of the gloss unit at over 2 ASD explained the appearance of the dark area on scanned images. When TEPA was higher than 0.07 M, the gloss unit of coatings was reversely proportional to the current density. These demonstrated that TEPA concentration could enhance the brightness of the coating in the low current area. Additionally, an increase in TEPA concentration up to 0.07 M led to an increase in glossiness regardless of current densities. For example, the glossiness obtained at 2 ASD was approximately 500, 800, and 900 with TEPA 0 M, 0.035 M, and 0.07 M, respectively. The difference in gloss unit between TEPA 0.07 and 0.1 M was insignificant, suggesting that the brightness of coatings approached a limitation at 0.07 M of TEPA.

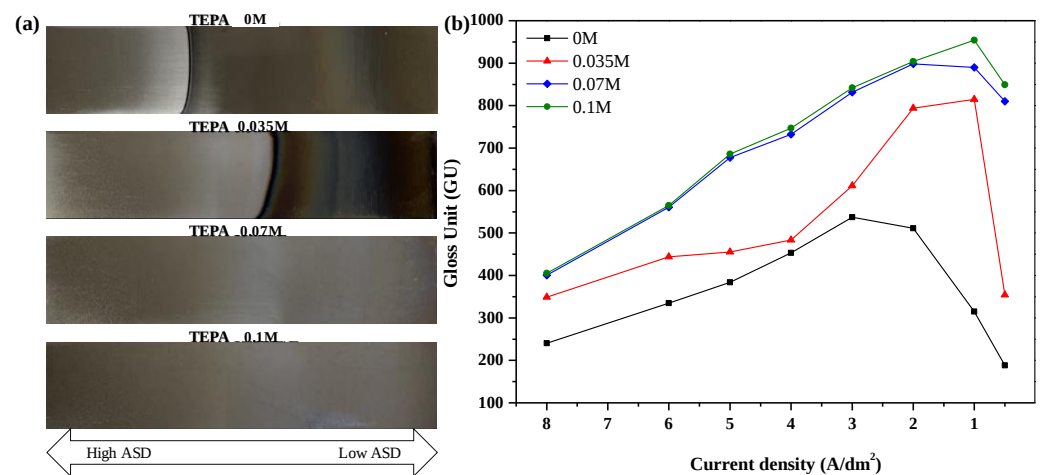


Figure 1. (a) Appearance of Zn-Ni alloy coatings obtained by Hull cell test with varying TEPA concentrations, and (b) glossiness as a function of current density (A/dm²) and TEPA concentration, measured in gloss units (GU).

3.2. Microstructure of Zn-Ni Alloy Coating

The XRD patterns of Zn-Ni plating layers with different TEPA concentrations and current densities are shown in Figure 2. Only phases of Fe and Zn-Ni alloys were detected from the XRD patterns. Fe phase is reflected at 44, 65, and 83°, indicating that the thickness of the Zn-Ni coating was not enough to shield the X-ray signal from the steel substrate. Other visible peaks are from Zn₁₁Ni₂ crystalline phase, which is a typical γ -phase crystal structure [32]. The reflection of Zn₁₁Ni₂ alloy was at 42.9°, 62.4°, and 78.7° corresponding to lattice planes of (411), (600), and (721), respectively. It was observed that TEPA concentration and current density mainly influenced the crystal orientation along (411) at 42.9° and (600) at 62.4°. Current densities lower than 1 ASD adversely affected crystallization, while a high TEPA concentration of 0.07 M and 0.1 M enhanced the intensity of (411) peak at 0.2 and 0.1 ASD and both intensities of (411) and (600) peak at 0.5 and 1 ASD. At 2 ASD, the (600) orientation was predominant regardless of TEPA concentration. With an increase in current density to 5 ASD, the intensity of (600) peaks decreased, while the intensity of (411) peaks increased with all TEPA concentrations. In conclusion, TEPA concentrations over 0.07 M improved the crystallization of the Zn-Ni alloy phase at low current density but did not have a significant effect on crystallization at high current density over 2 ASD.

The crystallite size was determined using the Scherrer equation, where $D = \frac{K \cdot \lambda}{\beta \cos \theta}$, with crystallite size (D) in nm, the shape factor (K), X-ray wavelength (λ) of 0.15406 nm for CuK α , full width at half maximum (β) in radians, and peak position (θ) in radians (Figure 3). As the (660) peaks were the most well-defined with all current densities, the crystallite size was calculated using full width at half maximum of the (660) peaks. The crystallite size decreased with increasing TEPA concentration until it remained constant at TEPA concentrations greater than 0.07 M. In addition, the increase in current density

induced the decline of crystallite size. The crystallite size with 0.07 M TEPA decreased from 37.5 nm to 12.5 nm when current density increased from 0.1 ASD to 5 ASD.

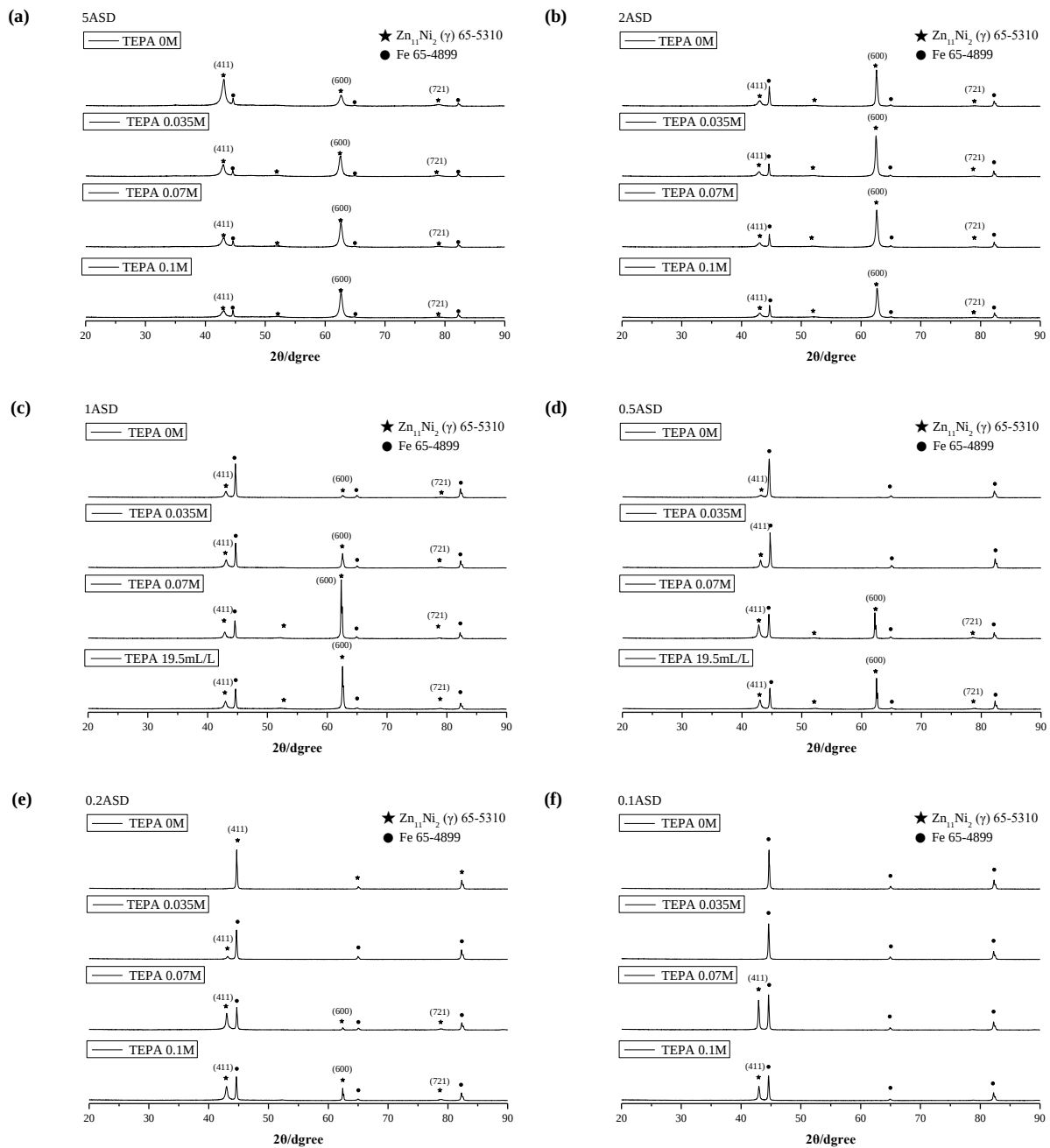


Figure 2. XRD patterns of Zn-Ni alloy coatings with different TEPA concentrations at (a) 5ASD, (b) 2ASD, (c) 1ASD, (d) 0.5ASD, (e) 0.2ASD, and (f) 0.1ASD.

Figure 4 shows the morphology of coating at 0.07 M TEPA with different current densities and at 2 ASD with different TEPA concentrations. The surface showed fine, nodular grains with good distribution, and no cracks or defects. The absence of porosity and the dense surface suggested hydrogen desorption during electrodeposition. In the case of 0.07 M TEPA, finer grains were observed at higher current densities. Meanwhile, an increase in TEPA concentration resulted in a finer microstructure of the Zn-Ni coating at 2 ASD, which was constant to what was obtained from crystallite size. It appeared that when the decrease in grain size caused by increasing TEPA concentration induced the increase in glossiness (Figure 1b), which agreed with previous studies [33].

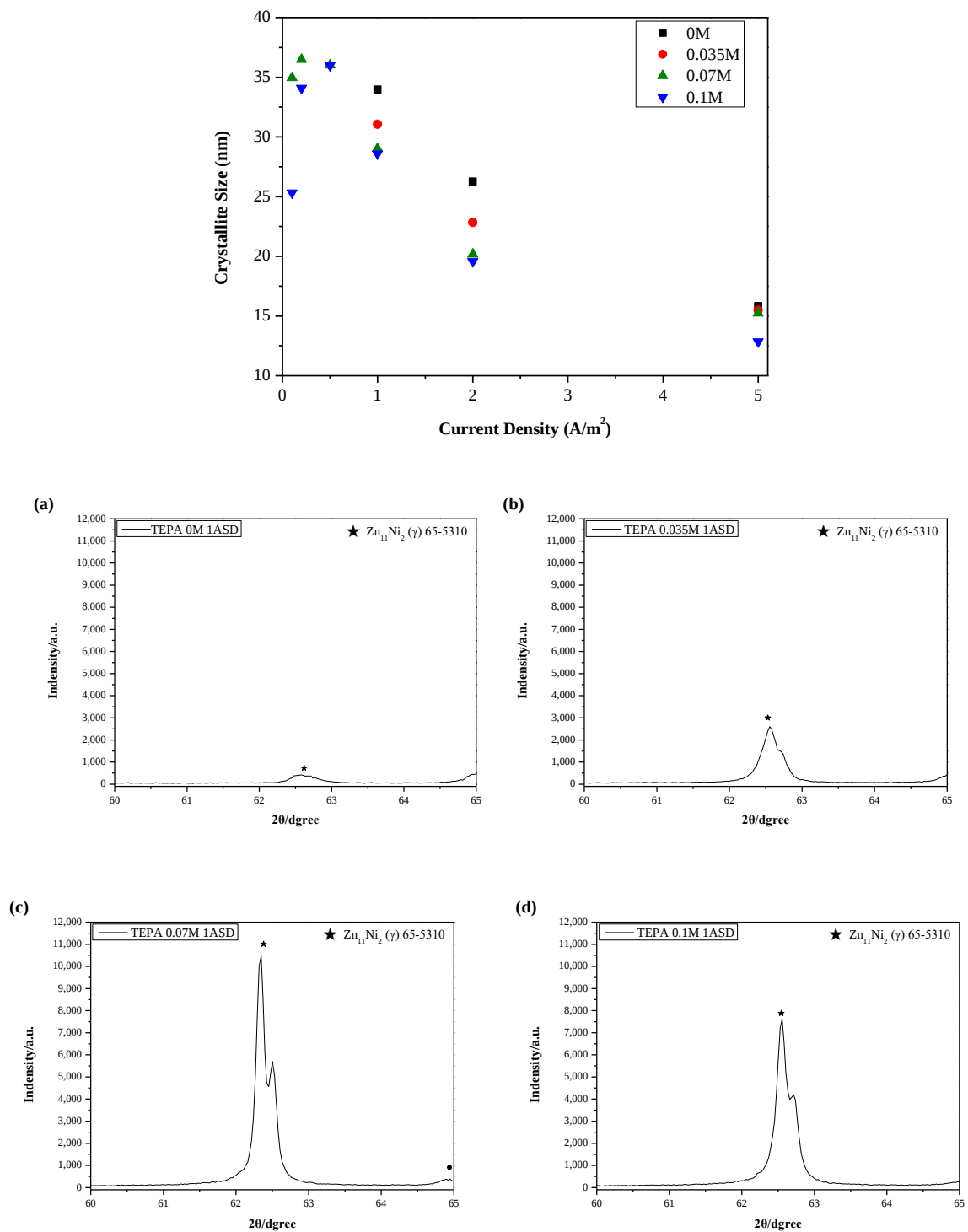


Figure 3. Cont.

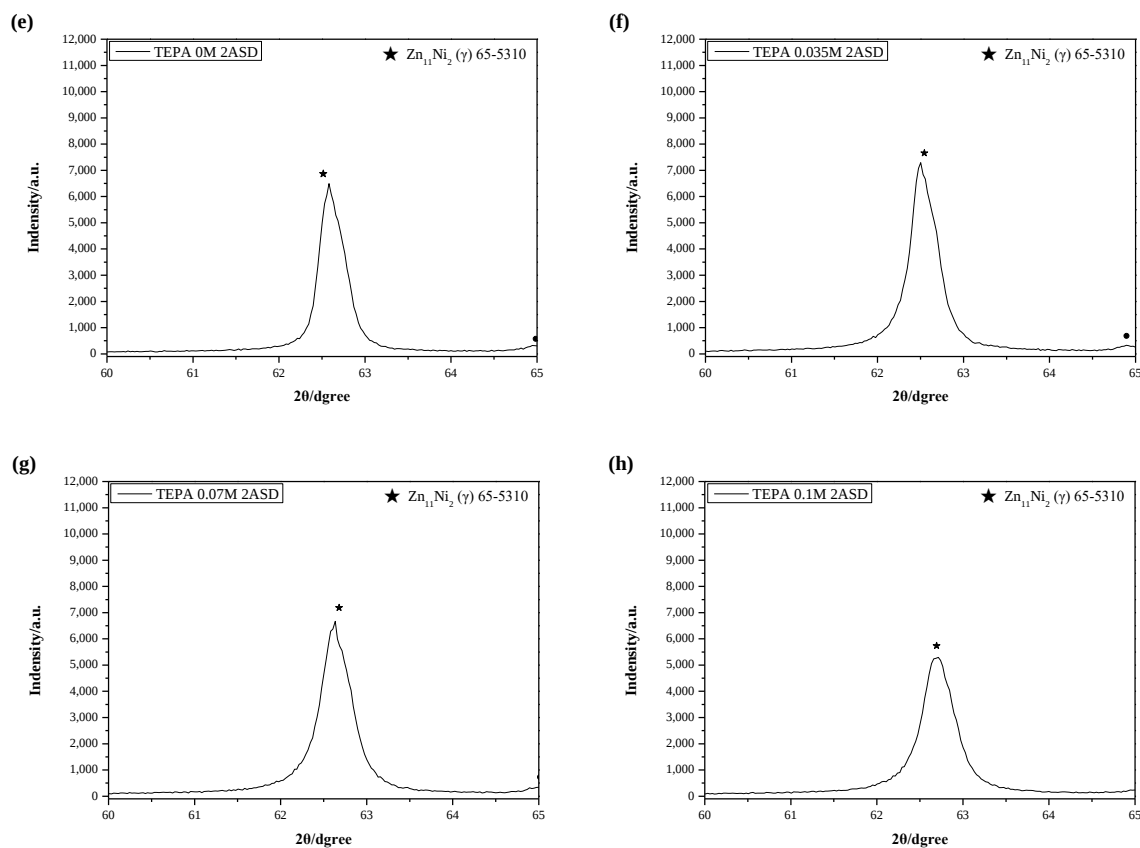


Figure 3. Crystallite size obtained from (600) peaks as a function of current density; enlargement of (600) peaks at 1 ASD with TEPA concentrations of (a) 0 M, (b) 0.035 M, (c) 0.07 M, and (d) 0.1 M, and at 2 ASD with TEPA concentrations of (e) 0 M, (f) 0.035 M, (g) 0.07 M, and (h) 0.1 M.

3.3. Electroplating Performance

Figure 5a shows the variation in thickness as a function of current density with different TEPA concentrations. The thickness was in a wide range from 1 μm to 11 μm . The decrease in thickness can be observed according to the decrease in current density. This could be explained by the distance between the anode and cathode because the higher anode-cathode distance in the Hull cell tank induces the lower current density as mentioned above. The longer anode-cathode distance causes the longer and more difficult transportation of cations, leading to the poor ability of cations to stick on the cathodic surface, the uneven cathodic surface, and the thinner coating. At current densities higher than 2 ASD, thickness decreased with the increase in TEPA concentration. For example, the thickness of Zn-Ni coating was 11, 10.5, 9.8, and 9 μm with 0, 0.035, 0.07, and 0.1 M, respectively. This was caused by the increase in TEPA concentration diminishing the diffusion rate of metal ions, thereby reducing the thickness [28]. For current densities lower than 2 ASD, most thickness values were identical, except for those with 0 M of TEPA concentration, which were lower than the others.

Furthermore, Figure 5b shows that Ni content decreased with the decrease in current density. In addition, the increase in TEPA concentration boosted Ni content at any current density. This result was supported by Ni content obtained through EDS mapping (Figure 6). A similar trend was observed in the case of EDS mapping (Figure 7), indicating that the increase in TEPA concentration significantly boosted the Ni content of Zn-Ni alloy coating. Notably, a TEPA concentration of 0.1 M could increase the Ni content by up to 20%, which is a high amount compared to previous studies [34]. The increase in Ni content owing to TEPA can be explained by the fact that TEPA acts as a complexing agent that binds with

Ni ions to prevent the precipitation of Ni hydroxide, thereby enhancing the deposition of metallic Ni on the cathode surface [27,28,34].

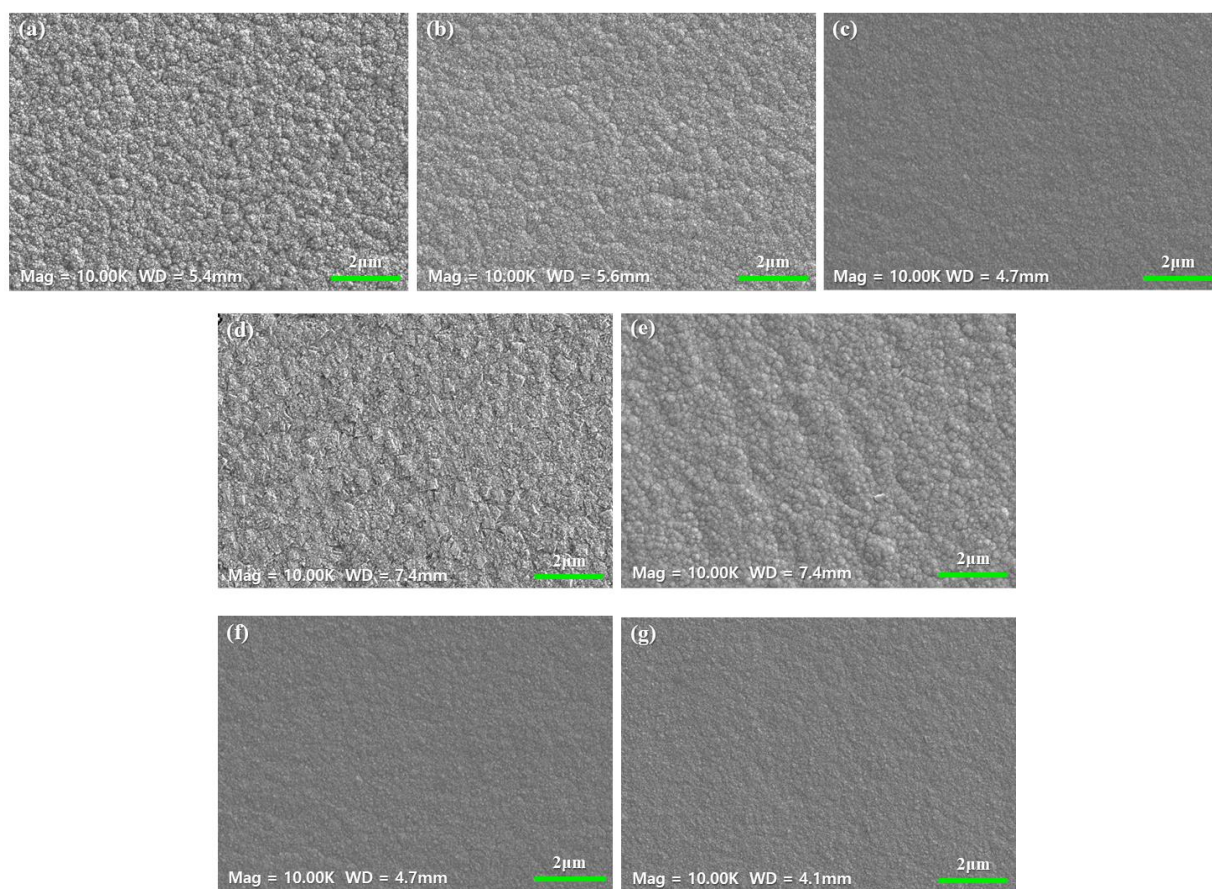


Figure 4. SEM images of Zn-Ni coating with 0.07 M TEPA at (a) 0.5 ASD, (b) 1 ASD, and (c) 2 ASD; and at 2 ASD with TEPA concentrations of (d) 0 M, (e) 0.035 M, (f) 0.07 M, and (g) 0.1 M TEPA.

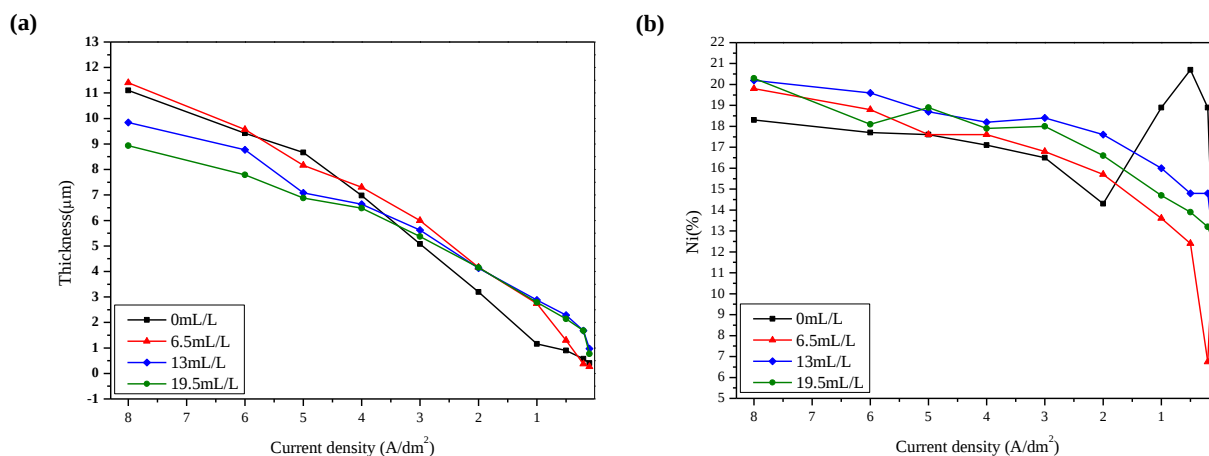


Figure 5. (a) The thickness of coating, and (b) Ni content obtained by XRF as a function of current density with different TEPA concentrations.

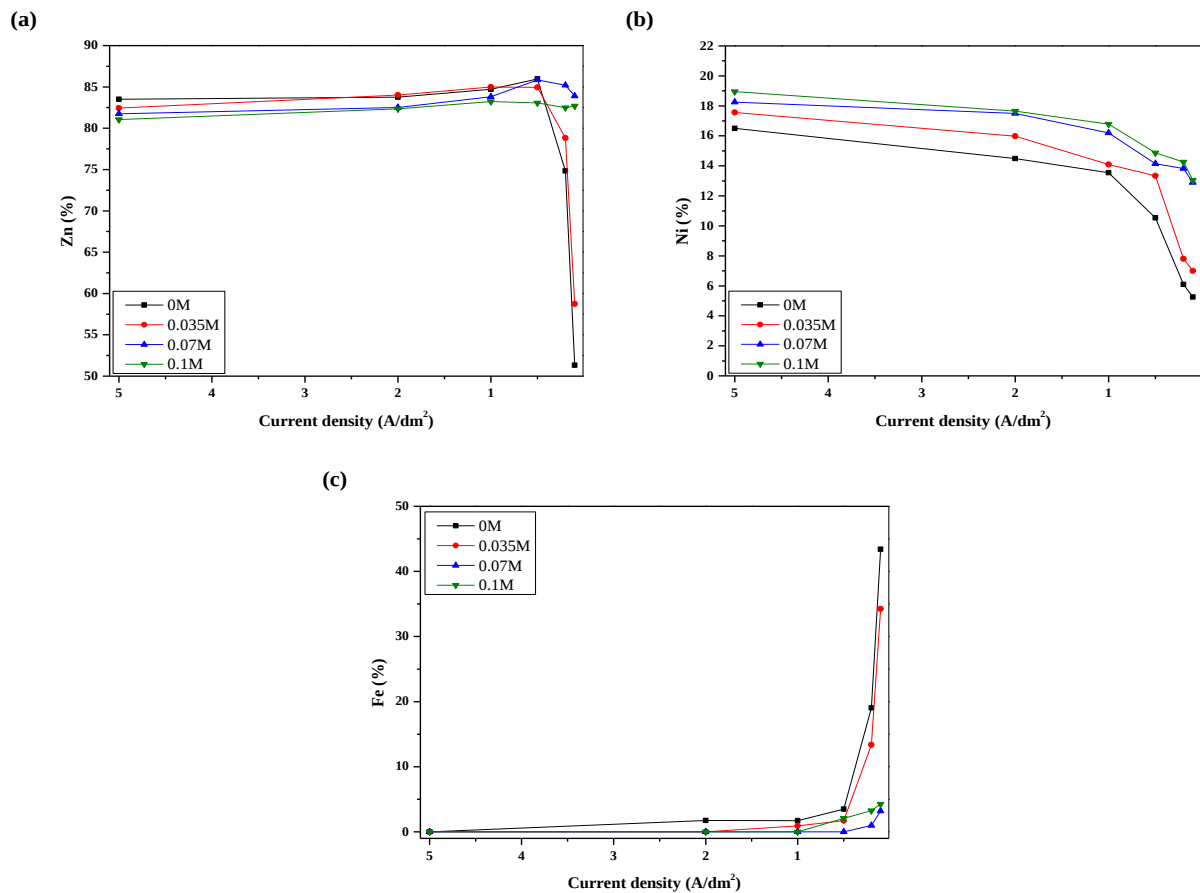


Figure 6. Content of (a) Zn, (b) Ni, and (c) Fe obtained by EDS mapping as a function of current density with different TEPA concentrations.

Electroplating allows creating a multi-component alloy coating at low temperatures. The anomalous co-deposition densifies an electrochemical deposition whereby the less noble metallic element is preferred to deposit from a bath consisting of various metallic ions, resulting in a higher content of the less noble metallic element in the deposit than other metallic elements. One previous study proved that the anomalous co-deposition occurs at a high current density, and the pH at the cathodic surface rises rapidly [35]. The rapid increase in surface pH causes the formation of hydroxides of the less noble metal, which adsorb on the cathodic surface, thereby suppressing the reduction of other metallic ions. This occurrence is recognized in the co-deposition of iron-group metallic elements, or iron-group elements with Zn or Cd [36]. The Zn-Ni alloy electrodeposition is called anomalous co-deposition, in which the less noble metallic element, Zn, is preferentially deposited.

To investigate the deposition behavior of each component of Zn-Ni alloy, the partial polarization curves of Zn and Ni deposition could be determined using the following method. The content of coulomb (q) was fixed (2.5 C), and the current density (i_a) of alloy deposition was varied (0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 50 ASD); hence, the deposition time was determined as follow $t = q/i_a$. By applying the determined time and current density, the potential could be recorded using the potentiostat. The partial current densities of each Zn and Ni electrodeposition were calculated from the element mass obtained by AAS and the chemical composition of the coating according to Faraday's laws of electrolysis using the formula: $i = \frac{mFv}{AtM}$, where i is the partial current density of element (A.cm⁻²), m is the amount of element (g), M is the molecular weight of element (g/mol), v is the valency of the ions, A is the surface area of the cathode (cm²) t is the time of electrodeposition (s), and F is Faraday constant (96,500 s.A/mol). For each sample, the electrochemical test was carried out 3 times, and the average values were calculated. Figure 8 displays

the partial polarization curves of Zn and Ni during Zn-Ni alloy electroplating at room temperature. For ease of visibility, the current density is presented as a function of potential on a logarithmic scale. The equilibrium potential of Zn E_{Zn}^{eq} is -1.27 V with pure Zn depositing at room temperature [17]. The Zn polarization curve rose at approximately -1.0 V, which is nobler than E_{Zn}^{eq} , suggesting underpotential deposition of Zn. The cathode potential subsequently shifted to the negative direction, which is less noble than E_{Zn}^{eq} , and the current density increased with shifting potential. A similar trend occurred during Ni deposition. Specifically, the partial current density for Ni deposition constantly increased from -1.0 V to potentials less noble than E_{Zn}^{eq} . Both the partial current densities of Zn and Ni depositions reached constant values at potentials more negative than -1.8 V, indicating that the deposition limitations of Zn^{2+} and Ni^{2+} ions are at -1.8 V. This agrees with the Butler-Volmer equation [37], which predicts four regions of a polarization curve, including a linear increase of current density with overpotential, exponential increase indicating pure activation, mixed control of activation and mass transportation, and a limiting diffusion current density. Furthermore, the current density of Zn deposition was higher than that of Ni deposition at all TEPA concentrations, which is constant to what was stated about the anomalous co-deposition. Additionally, the partial polarization curve did not significantly change with the change of TEPA concentration in both Zn and Ni deposition cases, indicating that TEPA did not significantly influence the electrochemical behavior of partial Zn and Ni deposition.

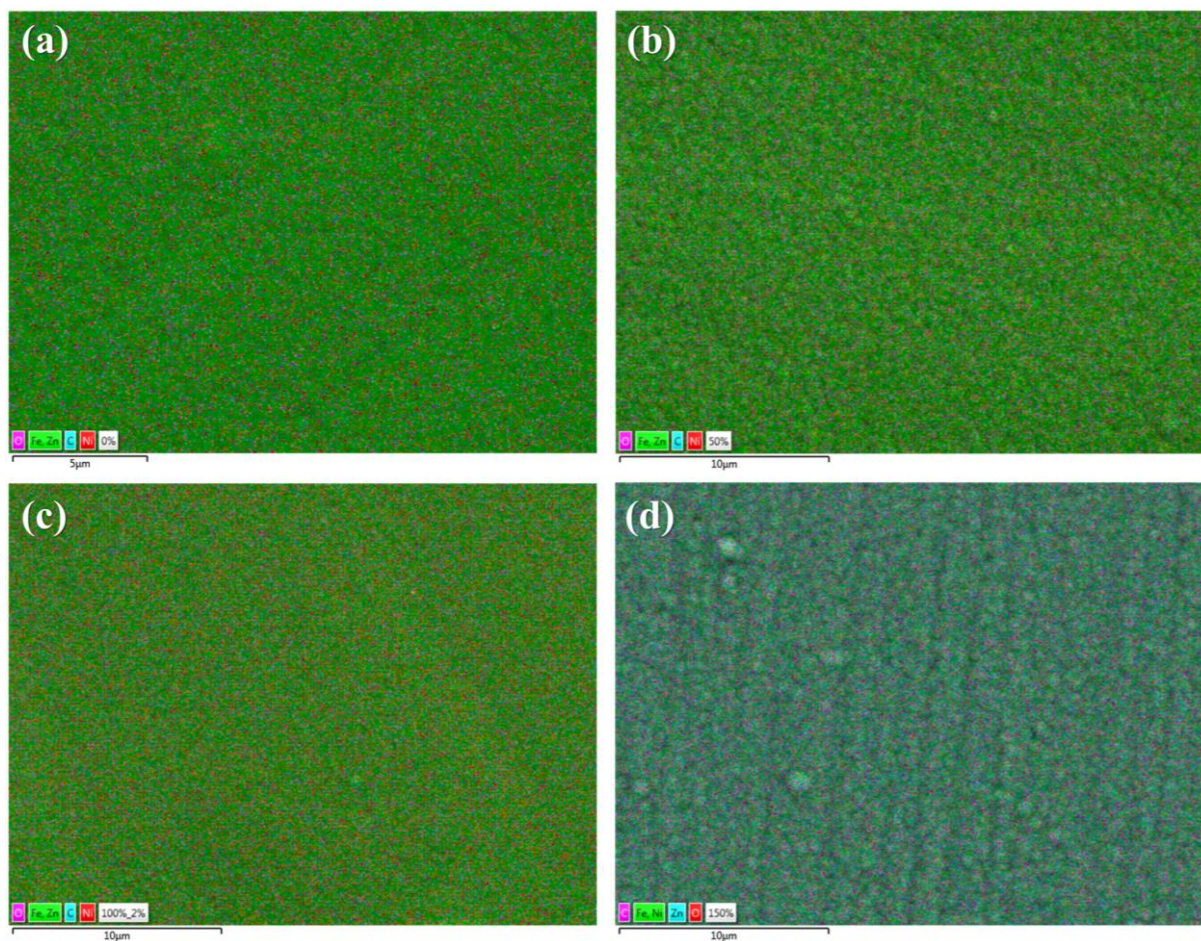


Figure 7. EDS mapping of Zn-Ni coating surface with TEPA concentrations of (a) 0 M, (b) 0.035 M, (c) 0.07 M, and (d) 0.1 M.

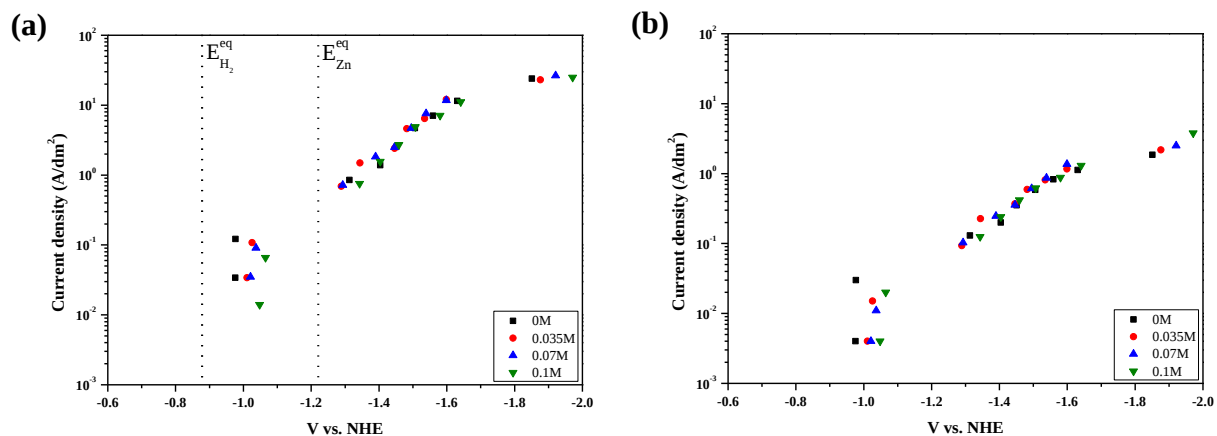


Figure 8. Partial polarization curves of (a) Zn, and (b) Ni.

4. Conclusions

This study aimed to investigate the impact of TEPA concentration on electrodeposited Zn-Ni alloy coatings. The results indicate that an increase in TEPA concentration from 0.035 M to 0.1 M led to the improved surface gloss of coatings at low current densities, as well as an increase in the crystallization of Zn-Ni alloy coating at low current density. While the crystallite size decreased with increasing TEPA concentration, the increase in TEPA concentration resulted in a coarser morphology of the Zn-Ni coating. Additionally, the increase in TEPA concentration led to a decrease in the thickness of coatings from approximately 10 μm to lower than 5 μm at a current density higher than 2 ASD. On the other hand, the variation in Ni content was proportional to the change in TEPA concentration, and the content of Ni could reach up to 20% at 8 ASD and TEPA concentration higher than 0.035 M. Notably, the study found that TEPA concentration did not influence the electrochemical behavior of Zn-Ni alloy deposition. In conclusion, this study highlights the vital role of TEPA concentration in controlling the properties of Zn-Ni alloy coatings. The findings have important implications for the development of high-performance coatings in a range of industrial applications. Further research is needed to explore the underlying mechanisms of the observed effects and identify strategies for further improving the properties of Zn-Ni alloy coatings.

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