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(IJIREV)**www.gaexcellence.com/ijirev**ELECTRODEPOSITION OF ZN–NI ALLOY COATINGS ON
ALUMINIUM SUBSTRATE: INFLUENCE OF DEPOSITION
PARAMETERS ON ADHESION STRENGTH**Siti Zairyn Fakurol Rodzi^{1*}, Tan Shen Yi²¹STEM Foundation Centre, Universiti Malaysia Terengganu, Malaysia siti.zairyn@umt.edu.my <https://orcid.org/0009-0009-9229-9938>²STEM Foundation Centre, Universiti Malaysia Terengganu, Malaysia a6468@ocean.umt.edu.my

*Corresponding Author

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Abstract:

Aluminium is widely used in various industrial and engineering applications due to its lightweight nature, high electrical and thermal conductivity, good mechanical strength, and excellent corrosion resistance, making it a preferred material in the automotive, aerospace, marine, and electronic industries. However, the formation of a natural oxide layer on aluminium surfaces often results in poor coating adhesion and reduced surface durability, leading to coating peel and weak interfacial bonding between the deposited metal coating and the substrate. This study aims to deposit zinc-nickel (Zn–Ni) alloy coatings onto aluminium substrates using a three-electrode electrochemical system to investigate the effects of deposition parameters on adhesion strength. Prior to deposition, the substrates were treated under zincate treatment to improve adhesion. The electrodeposition process was conducted at different parameters deposition times (10–20 min), temperatures (25–60 °C), and applied potential (–1.1 to –1.5 V). Electrochemical behaviour was analysed using cyclic voltammetry (CV), while coating adhesion was evaluated using the tape test method. The results revealed that deposition parameters significantly affected the coating performance. Higher temperature enhanced coating adhesion, with the strongest adhesion obtained at 60 °C. Shorter deposition time produced better adhesion compared to longer deposition periods, while an applied voltage of –1.3 V yielded the optimum adhesion strength. These findings demonstrate that optimization of electrodeposition parameters is essential for producing strongly adhered Zn–Ni coatings on aluminium substrates, thereby improving coating reliability and extending the potential application of aluminium components in demanding industrial environments.

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Keyword:

Aluminium Substrate, Adhesion, Coating, Electrodeposition



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Introduction

Electrochemical deposition is a widely used method to enhance the adhesion durability of metals. Aluminium, Al is treasured because it has lightweight and good conductivity properties. However, its natural oxide layer prompts to a weak adhesion of coating as reported by Fan et al. (2024). Zinc, Zn coatings provide sacrificial protection, but it can degrade quickly, while nickel, Ni can improve adhesion, strength and durability. Study cited by Lotfi et al. (2018) states that the combination of Zn–Ni alloys are of considerable interest as high adhesion and hardness and thermal stability and offers superior protection, though most research focuses on steel rather than Al foil (Luo et al., 2024).

Strong adhesion will produce a long-term protection and durability of the Al surface. One of the factors identified as to be responsible for the adhesive strength of metal coating with a metal substrate is the formation of a dispersion zone at the coating and substrate interface (Shtapenko et al., 2022). Although Zn–Ni alloy coatings have been widely studied for their excellent corrosion resistance, hardness, and wear performance, most previous findings mainly focused other metal substrates (Ding et al., 2025). Limited study has been given to the adhesion of coating using electrodeposition method of Zn–Ni alloys on Al substrates. Jiang et al. (2026) found that the presence of a naturally formed oxide layer on Al often results in low coating adherence, making the deposition process become tougher compared to conventional substrates. Furthermore, studies investigating the relationship between electrodeposition parameters and the adhesion behaviour of Zn–Ni coatings on Al remain inadequate.

Therefore, this research aims to investigate the electrochemical deposition of Zn–Ni alloy coatings onto Al substrates and evaluate how deposition parameters influence the adhesion performance of the coatings. The study will focus on optimizing key parameters such as the temperature, the current voltage and the deposition time to achieve optimum coatings. This research is important to relate the existing knowledge gap and unlatch the complete potential of Zn–Ni coated aluminium substrates for advanced applications in technology.

Literature Review

Electrochemical deposition, also known as electrodeposition, is a science that studies the deposition of materials onto a surface through the application of an electric field as reported by Sebastián et al. (2018). It becomes more popular due to its versatility, low cost, and ease of control over coating properties. Electrochemical deposition is widely used as a method for coating any conductive materials. There are many factors that can contribute to the adhesion of the coating. Among all, the different pre-treatments of substrates include solvent wiping,

sandblasting, phosphating, and galvanizing are the most extensively researched (Pathanatecha et al., 2019). Furthermore, the process parameters such as, types of electrolytes, current density, pH, and temperature are significantly affecting the performance and quality of the coatings. As reported by Duan et al. (2024), the light substrates like Al suitable for applications in packaging, electronics, and protective coatings. However, it requires the optimal electrochemical deposition to enhance its surface properties.

Even though it is difficult to directly electrodeposit the metal onto Al substrate due to its oxide layer, but it can be overcome by pre-treating it using zincating method right before electroplating process. The zincate pretreatment process is one of the most used methods in the electroplating industry as stated by Liu et al. (2024). The Zn-Ni alloy has high potential for the electrochemical deposition because of its exceptional compatibility with the electroplating process and the superior functionality of the final coating. Other than that, it is versatile as it can be efficiently deposited from aqueous solutions. Son, 2023 revealed that Zn–Ni alloy coatings are commonly electrodeposited from aqueous electrolyte baths because it is easier to control the thickness and chemical composition of the coatings. Therefore, Zn–Ni alloy electrodeposition is a promising approach to enhance the surface adhesion of Al substrates.

Research Methodology

Figure 1 shows the step-by-step process used to coat Al substrates with an alloy mixture of Ni and Zn. Firstly, the Al substrates were cleaned to remove the impurities and to ensure the coating can be deposited evenly on the cleaned surface. After that, using electrodeposition technique, which requires an electrical current to deposit the thin film out of a chemical bath. This flowchart illustrates an overview of the whole experiment, from the bath solutions preparation to adhesion test.

Preparations of Bath Solution and Surface Preparation

The Al substrates were prepared prior to electrodeposition through a surface treatment process. Each substrate was first immersed in the zincate solution for 60 seconds to remove the native oxide layer and promote adhesion. The substrate was then immersed in nitric acid solution for 60 seconds to remove excess Zn and stabilise the surface. After the acid treatment, the substrate was thoroughly rinsed with distilled water to eliminate any residual chemicals and was dried at room temperature before proceeding to the electrodeposition process. The bath solution was then prepared using 0.1 mol dm^{-3} mixture of the nickel sulphate, NiSO_4 , zinc sulphate, ZnSO_4 , sodium acetate, CH_3COONa and sodium sulphate, Na_2SO_4 solutions. The positively charged metal particles, specifically zinc (Zn^{2+}) and nickel (Ni^{2+}) cations were important prior to the deposition, meanwhile CH_3COONa and Na_2SO_4 were working as spectator's ions to complete the chemical bath.

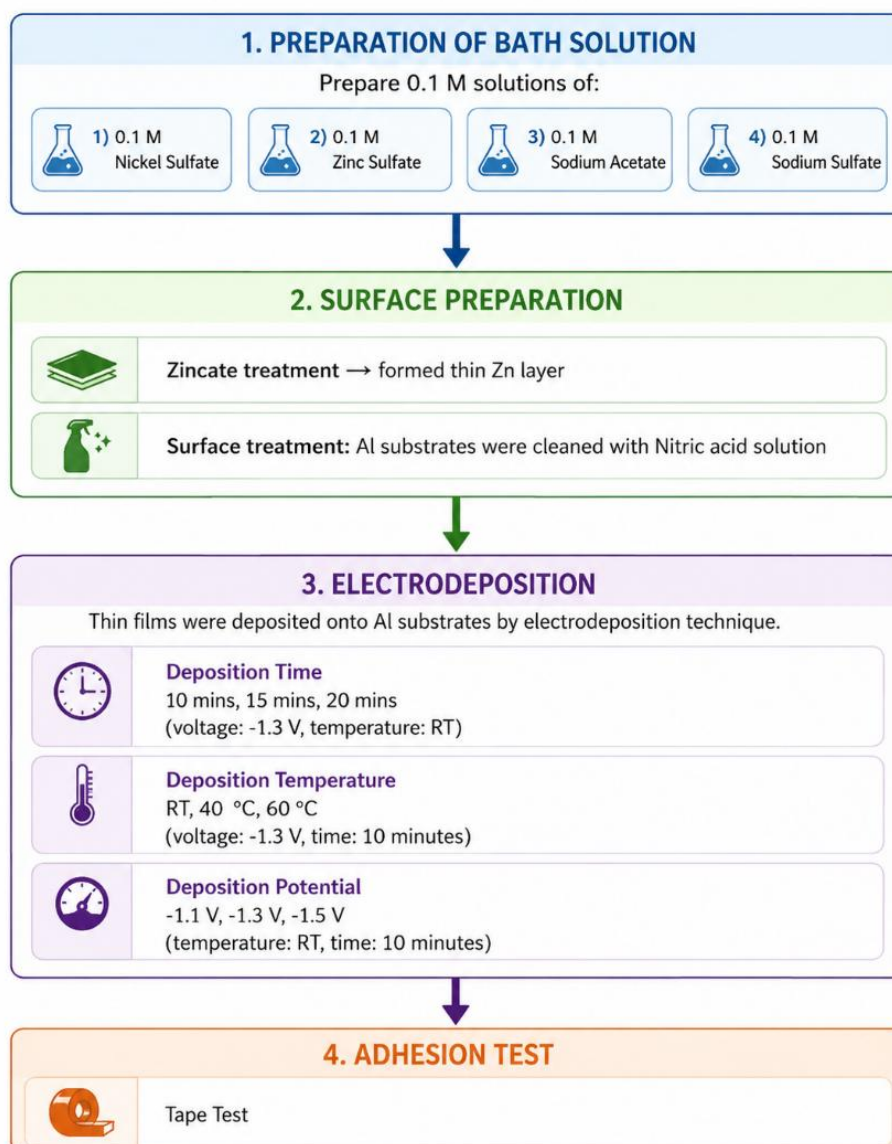


Figure 1: Experimental Workflow for the Electrodeposition of Ni-Zn Coatings onto Treated Aluminum Substrates

Electrodeposition Of Zn-Ni Coating

The electrodeposition of Zn-Ni alloy was carried out in a three-electrode potentiostat (Aut302FRA2) as illustrated in Figure 2, where the Al substrate and platinum, Pt rod were served as a working electrode and counter electrode respectively. Meanwhile, Ag/AgCl electrode served as a reference electrode. The distance between all these 3 electrodes had remained constant.

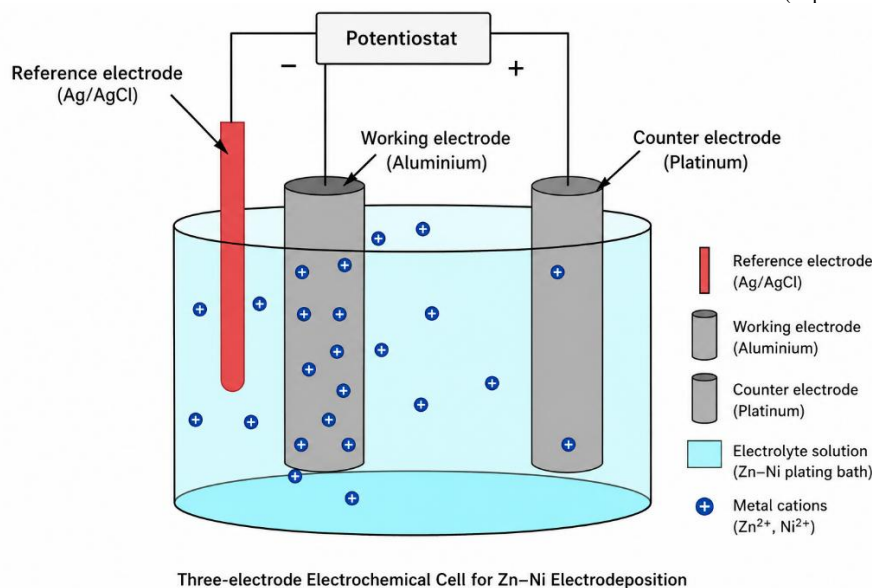


Figure 2: Schematic Diagram of the Three-Electrode Electrochemical Cell Used for Zn-Ni Electrodeposition

There were three important parameters involved prior to the electrodeposition of Zn-Ni alloy on the Al substrate. Firstly, the deposition time was varied at 10, 15, and 20 minutes while keeping the voltage fixed at -1.3 V and was carried out at room temperature. Secondly, the effect of deposition temperature was observed at 25 °C, 40 °C, and 60 °C, while the voltage was held constant at -1.3 V for 10 minutes duration. Lastly, the deposition potential was varied between -1.1 V, -1.3 V, and -1.5 V, at a fixed time at 10 minutes with constant room temperature.

Adhesion Test

After the deposition process, each sample was marked using a pencil line to set the location of the coating area to be tested. Prior to application, the adhesive tape was applied evenly onto the coating surface. A pressure was applied using a finger onto the coating surface to ensure all trapped air was removed and to have a proper contact. After that, the tape was pulled at a 180° angle in one fast and smooth motion. The images of before and after the adhesion test of the coating areas were clearly observed.

Results

Cyclic Voltammogram, CV

Prior to the electrochemical deposition of Zn-Ni coating, a cyclic voltammogram, CV analysis was carried out to determine the reduction and oxidation process occurred during the deposition process of Zn-Ni coating on Al substrate at room temperature. Figure 3 shows the CV of that was carried out in a three-electrode electrochemical cell in a bath solution by scanning the potential from 0 V to -2.2 V back to 0 at a scan rate of 50 mV/s.

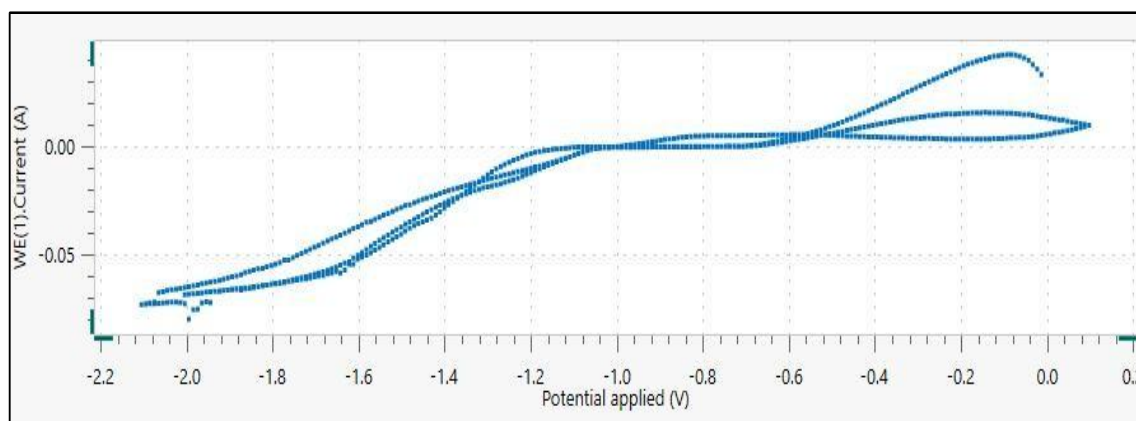


Figure 3: Cyclic Voltammogram of Aluminium substrate in a Three-Electrode Electrochemical Cell

The CV curve showed that during the forward scan from 0 V to -2.2 V, the current constantly decreases which proved the present of cathodic processes. Significantly, the reduction in the current can be observed as early as at -0.8 V, and keep changing to more than -1.2 V, indicating the reduction of the Zn^{2+} and Ni^{2+} ions. There were no clear and sharp reduction peaks which indicated that the deposition process might be led by mixed control instead of diffusion control only. The overlapped between the cathodic and anodic branches suggested the potential at which stable nucleation of the Zn-Ni alloy occurs on the Al substrate. The significant separation between the reduction and oxidation processes, indicates that the Zn-Ni electrodeposition involves nucleation and growth mechanisms at -1.3V (Liu et al., 2020).

Visual Assessment of Coating Adhesion via Tape Test

Effect on Deposition Time

Table 1 shows the images of adhesion test results of Zn-Ni alloy coatings deposited on Al substrates at different deposition times of 10, 15, and 20 minutes. The adhesion test was carried out using the tape test method by comparing the coating surface before and after the test. The observation has also been carried out on the appearance of the Scotch tape after removal as well. For the coating deposited at 10 minutes, the coating surface remained mostly unchanged after the adhesion test. Only very small traces of coating material were observed on the Scotch tape, indicating that the Zn-Ni coating has strong adhesion to the Al substrate. The better adhesion between the coating and substrate is due to relatively thin coating deposited at shorter deposition time. Meanwhile, the sample that prepared at 15 minutes deposition time had slight peeling and sample at 20 minutes had more coating residue that can be observed on the tape.

Table 1: Tape Adhesion Results by Deposition Time

Deposition Time (minutes)	Before Adhesion Test	After Adhesion Test	Appearance of Scotch Tape After Adhesion Test
10			
15			
20			

The adhesion strength decreases at longer deposition times is most probably due to the thickness of the coating layer, which can weaken the bonding between the Zn–Ni coating with the Al substrate Loperena et al., (2022). Thus, the adhesion test results suggest that the adhesion can be improved by shorten the deposition time.

Effect on Deposition Temperature

Table 2 shows the image results of the adhesion test for Zn–Ni alloy coatings deposited on Al substrates at different temperatures of 25 °C, 40 °C, and 60 °C. Sample prepared at 25 °C showed a very poor adhesion as the significant coating residue can be observed on the tape after the adhesion test. It can be assumed that the electrochemical reactions will occur more slowly, which is hard to produce a dense and well-adhered coating layer. However, when the deposition temperature is increased to 40 °C and 60 °C, the coating surface shows better stability after the adhesion test. Sample at 60 °C produced minimal residue of coating material observed on the tape.

Table 2: Tape Adhesion Results by Deposition Temperature

Temperature (°C)	Before Adhesion Test	After Adhesion Test	Appearance of Scotch Tape After Adhesion Test
25			
40			
60			

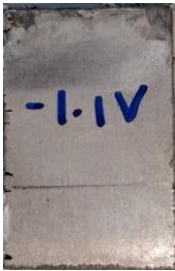
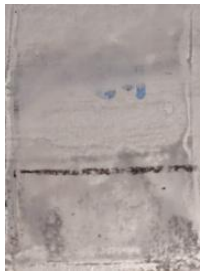
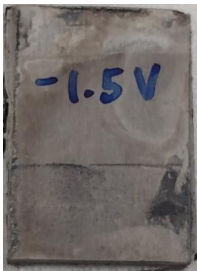
This indicates that the higher temperature, the higher the production of ion diffusion and deposition kinetics. This will allow the Zn–Ni alloy to form a more uniform and compact coating layer that deposited more strongly to the Al substrate. This suggests that a better coating growth will promote to stronger bond between Zn–Ni alloy coating to the substrate at a higher temperature Tan et al. (2021).

Effect on Deposition Potential

Table 3 shows the results of the adhesion test for Zn–Ni alloy coatings deposited on aluminium substrates under different applied voltages of -1.1 V, -1.3 V, and -1.5 V. For the sample deposited at -1.1 V, the formation of deposition of Zn–Ni alloy layer on the Al substrate is barely seen, which also produced insignificant coating removal on the tape. This indicates that the adhesion between the Zn–Ni coating and the aluminium substrate is very moderate. At lower applied voltage, the electrochemical driving force for the reduction of Zn^{2+} and Ni^{2+} ions are relatively weak, which leads to slower deposition. However, when the voltage is increased to -1.3 V, the coating surface remains mostly unchanged after the adhesion test. This evidence strongly proved that an optimal electrochemical driving force that promotes uniform nucleation

and growth of the Zn–Ni alloy coating, resulting in stronger bonding between the coating and the aluminium substrate. However, sample prepared at -1.5 V, showed more coating residue on the tape after the adhesion test. This concludes that the adhesion strength falls at higher applied voltage. The stronger applied potential promotes the rapid coating growth and the formation of a rougher or less stable coating layer (Cho et al., 2025). Other than that, the process of hydrogen evolution may also contribute to a negatively affect coating adhesion.

Table 3: Tape Adhesion Results by Deposition Potential

Potential (V)	Before Adhesion Test	After Adhesion Test	Appearance of Scotch Tape After Adhesion Test
-1.1			
-1.3			
1.5			

Overall, an optimal voltage is necessary to produce a uniform deposition and strong bonding between the metal coating and the substrate.

Conclusion

This study investigated the main objective which was to examine how the different in electrodeposition parameters such as deposition time, temperature, and applied voltage affect the adhesion strength. The results showed that deposition parameters significantly affected the coating performance where higher temperature enhanced coating adhesion, with the strongest

adhesion obtained at 60 °C. Shorter deposition time at minimum of 10 minutes produced better adhesion compared to longer deposition durations, while an optimum applied voltage of –1.3 V produce good adhesion strength. These findings suggest that optimization of electrodeposition parameters is important to produce strong adhesion of Zn–Ni alloys coatings on Al substrates.

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Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. Siti Zairyn Fakurol Rodzi was responsible for the conceptualization, methodology, and overall supervision of the study. Tan Shen Yi handled data collection, analysis, and interpretation of results. Siti Zairyn Fakurol Rodzi and Tan Shen Yi contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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