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Research Article

Influence of Electroplating Time on the Hardness Properties of Nickel-Coated Aluminum

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Abstract

This study investigates the effect of electroplating duration on the hardness and coating thickness of nickel layers deposited on aluminum substrates. Nickel electroplating was performed with immersion times of 17, 34, 51, and 68 min to evaluate the correlation between deposition time, microstructural development, and mechanical enhancement. Microstructural analysis revealed a progressive increase in coating thickness from 3 μm, 7 μm, 11 μm, to a maximum of 44 μm as plating duration increased. Correspondingly, surface hardness exhibited a substantial rise, with untreated aluminum showing 69.44 HV, while electroplated specimens achieved 118.32 HV, 191.32 HV, 258.40 HV, and 418.62 HV, respectively. This increase of up to 502% demonstrates that longer electroplating durations produce denser and finer nickel microstructures, contributing significantly to surface strengthening. The findings confirm that nickel electroplating is an effective method for enhancing the mechanical performance and surface quality of aluminum, with deposition time serving as a critical parameter in optimizing coating characteristics.

Keywords: *Aluminum alloy, nickel electroplating, deposition time, coating thickness, hardness*

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INTRODUCTION

Aluminum and its alloys are widely used in automotive, aerospace, and construction industries due to their lightweight and excellent corrosion resistance. However, their relatively low hardness and poor wear resistance limit their application in components subjected to high mechanical stress. To overcome these limitations, surface modification techniques such as electroplating have been extensively employed. Nickel electroplating, in particular, is recognized for its ability to improve hardness, wear resistance, and corrosion protection of aluminum substrates, making it a preferred choice in industrial applications [1].

Electroplating involves the deposition of a metallic layer onto a substrate through an electrolytic process. Among the critical parameters influencing coating quality are current density, bath composition, temperature, and plating time [2][3]. While numerous studies have examined the effects of electroplating conditions on coating adhesion and corrosion resistance, the specific influence of plating time on mechanical properties especially hardness remains an area requiring deeper investigation [4][5]. Plating time directly affects coating thickness, microstructure, and defect formation, which in turn determine the mechanical performance of the coated material [6].

Previous research has highlighted the importance of optimizing electroplating duration. Hidayah Fajria et al. [7] reported that nickel electroplating on AA2024 aluminum achieved maximum hardness at 10 minutes (198.31 HV), followed by a decline at 20 min (132.81 HV), attributed to pitting defects and uneven deposition. Similarly, Akhyar et al. [8] observed that hardness initially increased with plating time, peaking at approximately 25 min before decreasing with prolonged exposure. These findings suggest that excessive plating time may lead to internal stresses, micro-cracks, or porosity, reducing the coating's effectiveness.

Although previous research has shown that excessively long electroplating durations can reduce hardness due to the formation of micro-defects, the extension of the plating time in this study was undertaken to evaluate the mechanical stability of the nickel coating under more controlled process conditions. The extension of the plating time was intended to investigate whether the control of parameters such as current density, electrolyte stability, and a uniform deposition rate could suppress the formation of porosity and microcracks that typically arise during prolonged plating. Furthermore, a longer plating time allows for a comprehensive observation of microstructural evolution, including the transition from the initial nucleation stage to the growth of a more mature coating, as well as a more stable distribution of residual stresses. This approach is crucial for verifying whether the phenomenon of hardness reduction during prolonged plating is inherent to the process duration or is more influenced by sub-optimal plating conditions, as suggested in several recent studies on the electroplating of nickel and aluminum alloys [9–11].

This study aims to systematically investigate the effect of electroplating time variations on the hardness of nickel-coated aluminum. By analyzing different time intervals, we seek to identify the relationship between deposition duration and hardness performance, providing insights for industrial applications where durability and surface strength are critical. The findings are expected to contribute to the development of optimized electroplating processes for aluminum-based components, ensuring improved functionality and extended service life.

METHODS AND ANALYSIS

The substrate used in this study was an Al100 aluminum alloy in the form of a cylinder with a diameter of 14 mm and a thickness of 7 mm. The chemical composition of the specimens is shown in Table 1. In order to ensure an optimal surface finish prior to the coating process, the specimens are first sanded using Wipro sandpaper with various

Table 1. Chemical composition of aluminum alloy substrates (%)

Al	Si	Cu	Zn	Mg
92.44	4.59	1.17	0.77	0.58

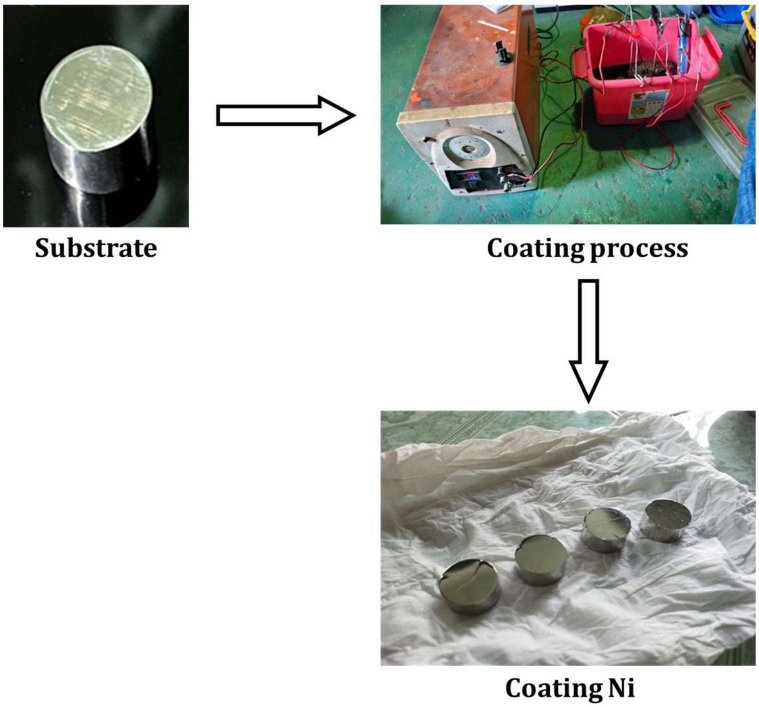

Figure 1. Schematic of the nickel plating process using the electroplating method.

grit sizes, ranging from 200, 300, 400, 500, 600, 800, 1000, 1500 and 2000. Following the sanding process, the specimen surfaces are polished using Autosol to remove scratches and achieve a smooth finish.

The plating process is carried out by preparing an electrolyte solution for nickel plating consisting of 260 g/l $NiSO_4$ (nickel sulphate), 50 g/l NiCl (nickel chloride) and 45 g/l boric acid. The electrolyte solution used for nickel plating amounted to 3 litres and was maintained at a temperature of 50-60 °C, whilst the pH of the solution was 4-4.5. Figure 1 illustrates the nickel plating process, which utilised a plastic box measuring 251 x 199 x 105 mm as the plating solution tank and an aluminum alloy as the cathode. The anode is connected to a rectifier, whilst copper is used to hold the substrate. The nickel plating process is carried out at a constant voltage of 3 volts, and the plating time varies between 17, 34, 51, and 68 min. This time range was selected to represent the nucleation, stable growth and maturation phases of the coating, in order to evaluate the evolution of the microstructure and mechanical properties of the nickel coating [10][12][13].

After the electroplating process, the samples were subjected to a coating thickness test on a cross-section using an optical microscope. Surface hardness, in this case Ni coating, was measured using a Vickers microhardness tester (type HVS-1000Z) with a diamond pyramid (136°) using a load of 0.098 N and a penetration time of 5 seconds. The average hardness value was recorded from 5 measurements taken on the Ni coating surface at random positions.

RESULTS AND DISCUSSIONS

The results showed that the coating time significantly affected the layer thickness and structural integrity. Figure 2 shows that the layer thickness increased on the aluminum substrate at electroplating durations of 17, 34, 51, and 68 min. At 17 min, the nickel layer is very thin (≈3 μm), which may provide minimal improvement in hardness. Increasing the time to 34 min results in a thicker nickel layer (≈7 μm) and a zincate layer of 9 μm, improving adhesion and uniformity. At 51 min, the nickel layer reaches 11 μm, suggesting stable deposition and better coverage. At 68 min, the nickel coating becomes substantially thicker (≈44 μm), while the zincate coating measures 15 μm.

Figure 3. illustrates the cross-sectional microstructure of nickel layers. Although thicker coatings generally enhance corrosion resistance, excessive thickness can introduce internal stresses, micro-cracks, and porosity, reducing mechanical performance [7][8].

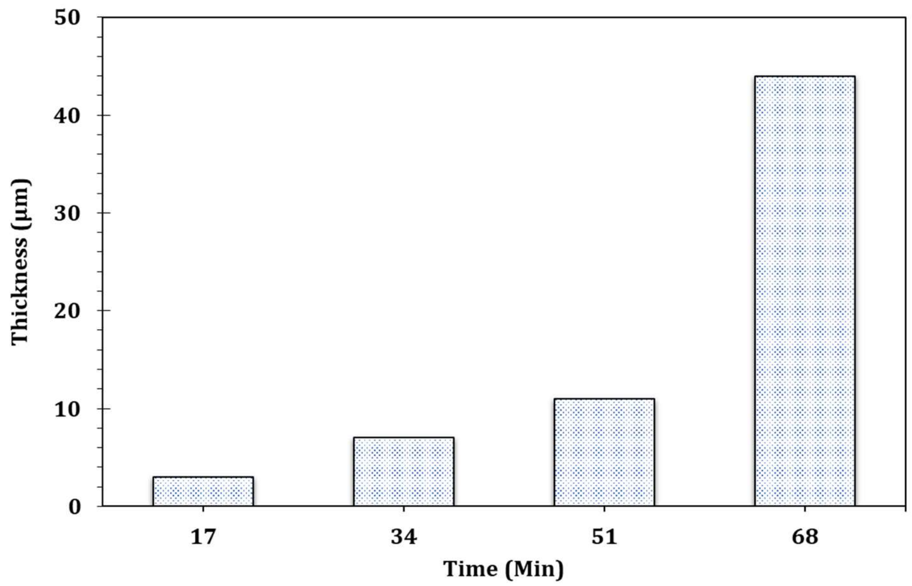

Figure 2. Thickness of nickel coating on aluminum with variations in electroplating process time.

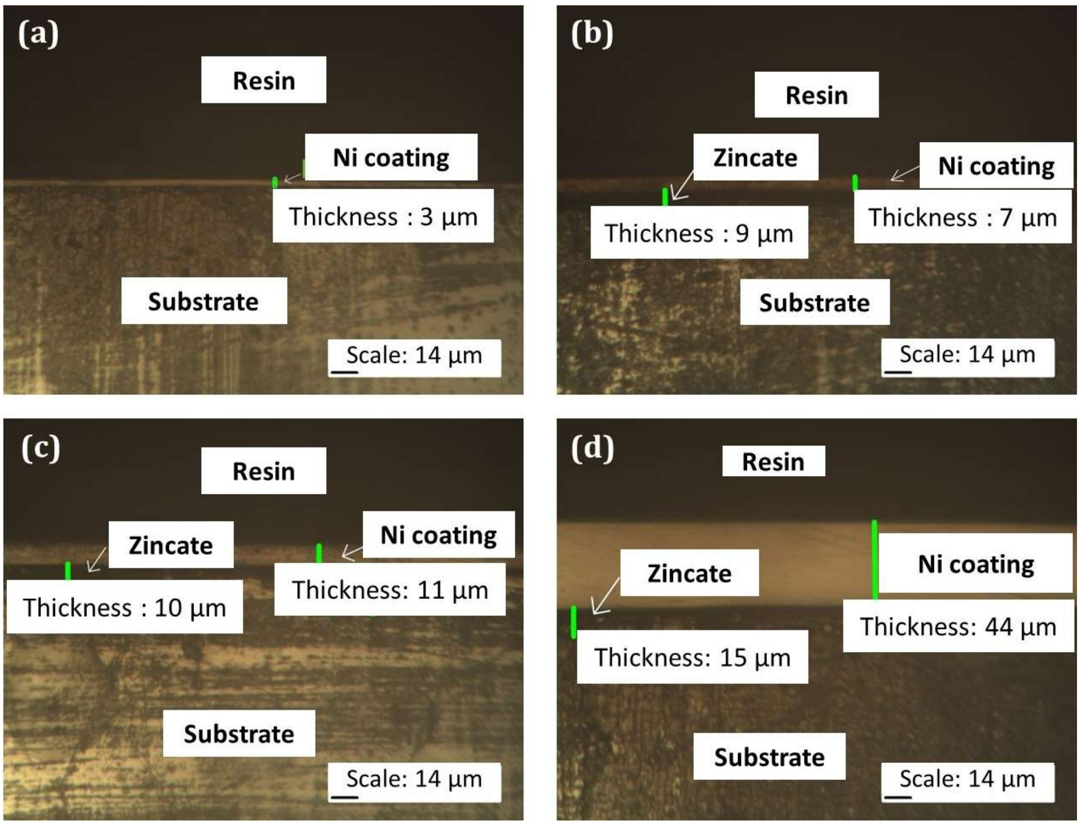

Figure 3. Cross-sectional microstructure of nickel coatings with electroplating processes at (a). 17, (b). 34, (c). 51, and (d). 68 min.

Previous studies confirm that electroplating time strongly influences hardness and coating quality. Fajria et al. [7] reported maximum hardness at shorter durations, followed by a decline at longer times due to defects. Akhyar et al. [8] and Mohammed et al. [14] observed similar trends, where hardness increased up to an optimal point before decreasing. Krim et al. [1] emphasized that prolonged deposition combined with annealing affects intermetallic phase formation, which can improve hardness but also increase brittleness. Electroless nickel-boron coatings exhibit comparable behavior, where extended deposition leads to porous structures [15]. Zincate layers play a critical role in adhesion, but their increasing thickness may contribute to stress concentration [16]. Studies on porosity and uneven growth further highlight the need for optimized plating time [1,17,18] . Therefore, determining an optimal electroplating duration is essential for balancing hardness, adhesion, and coating integrity.

Hardness Coatings

Figure 4 shows a significant increase in the hardness of the nickel coating as the electroplating time increases, from 69.44 HV at 0 min, increasing to 118.32 HV at 17 min, 191.32 HV at 34 min, 258.40 HV at 51 min and up to 418.62 HV at 68 min. This increase correlates with the growth in thickness and the densification of the coating's microstructure. As the deposition process proceeds, a finer grain structure forms and internal stresses accumulate, which together increase the resistance to plastic deformation and strengthen the nickel coating [11].

In contrast to the findings of Akhyar et al. [8] and Fajria et al. [7], which indicated a decrease in hardness following excessively long electroplating durations due to porosity and irregular layer growth, the results of this study show that hardness remains stable even when the plating time is extended. This stability is believed to be related to the optimal control of process parameters, such as current density, temperature, electrolyte stability, and the use of additives, which maintain a uniform deposition rate and suppress the formation of microdefects [19][20]. Under these conditions, the nickel coating can grow homogeneously with relatively fine grain size, so that the grain refinement-based strengthening mechanism remains dominant and is supported by a more uniform residual stress distribution, which prevents cracking and delamination [21][22].

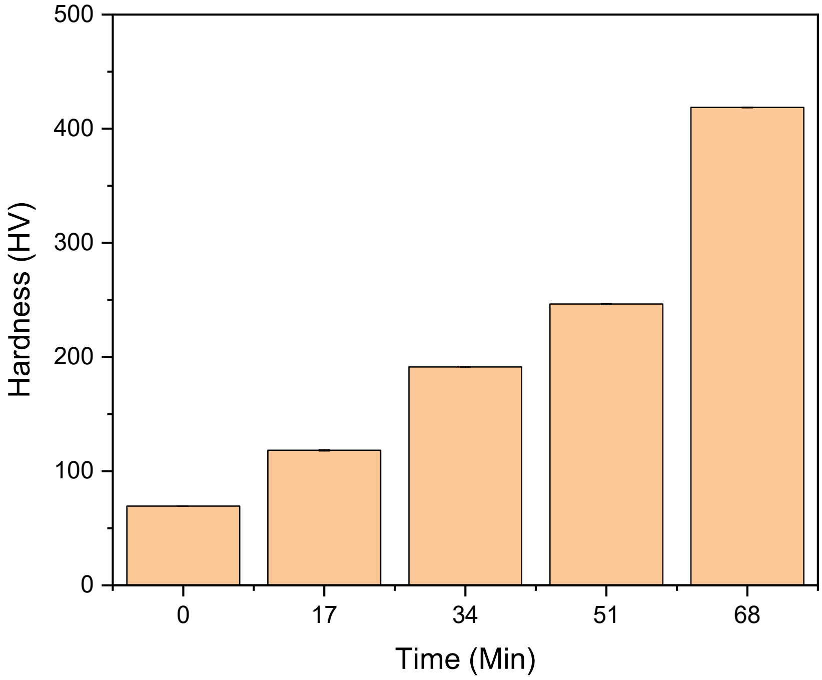

Figure 4. Hardness of aluminum before and after nickel plating with variations in electroplating process time.

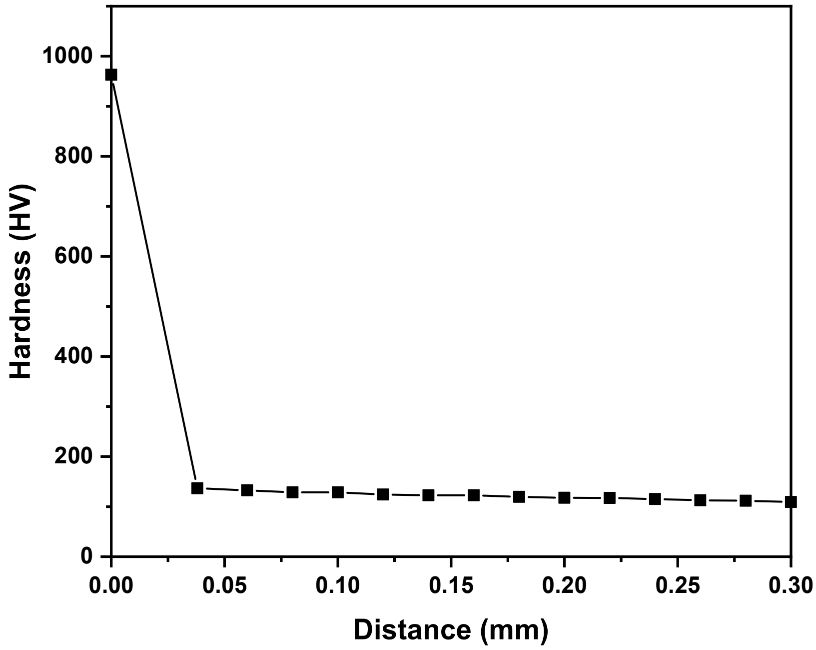

Figure 5. Hardness cross-section of aluminum specimens after nickel coating by electroplating for 68 min.

Thus, the increase in hardness is consistent with various studies, which confirm that coating time is a key parameter in improving the mechanical properties of nickel-coated aluminum. However, excessive duration can increase the risk of porosity and internal stress, so optimisation is necessary to maintain a balance between hardness, thickness and coating integrity.

Figure 5 shows the hardness profile on the cross-section of the electroplated nickel layer shows two distinct microstructural zones. At a distance of 0 mm, the hardness value reaches ~950-1000 HV, indicating the formation of an ultra-fine (nanocrystalline) microstructure in the early stages of deposition. This zone generally has a very high nucleation density, resulting in very small grains, which significantly increase hardness through the Hall-Petch mechanism. This phenomenon is consistent with recent reports showing that electroplating parameters such as current density, electrolyte composition, and brightener additives affect the formation of fine-grained nickel layers with a substantial increase in hardness [23].

Significant decrease in hardness at a depth of approximately 0.038 mm indicates a transition from a nanocrystalline surface zone to a coarser and more stable microstructure in the interior. In this zone, grain growth mechanisms begin to dominate over initial nucleation, leading to an increase in grain size and a reduction in residual stress. Recent studies on nickel plating have shown that deposition parameters such as current density and electrolyte composition can induce grain coarsening in the underlying layer, thereby reducing hardness relative to the surface layer [24]. After passing through the transition zone, hardness values tend to stabilise up to a depth of 0.30 mm, indicating a more homogeneous microstructure, typically consisting of larger columnar or equiaxed grains. This pattern is consistent with reports in a recent review stating that electroplated nickel layers typically exhibit extreme mechanical properties at the surface due to ultra-fine grain size and high residual stress, whilst the interior shows lower and relatively constant hardness [25][26].

In addition, several recent studies emphasise that the hardness of nickel coatings can increase significantly if the coating contains nanostructures or if composite additives such as graphene, MoS_2, or carbon nanoallotropes are used. However, these studies still show that the transverse hardness profile generally maintains the same pattern: maxi-

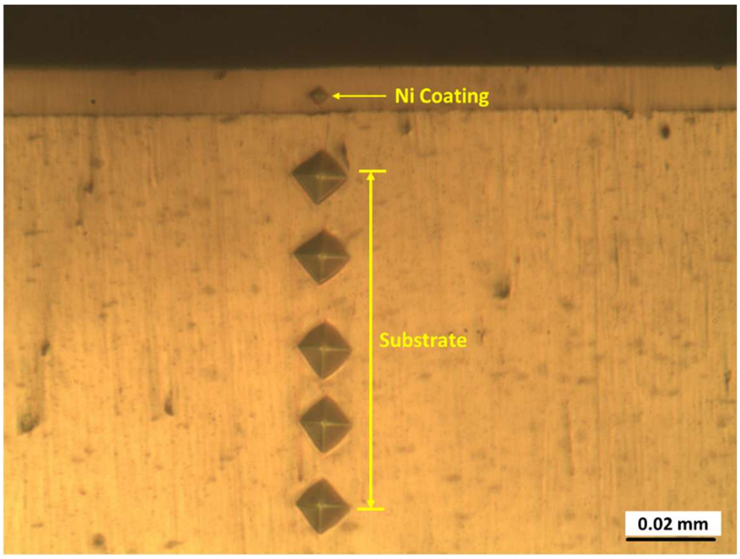

Figure 6. Vickers indentation marks on the cross-section of an aluminum specimen after being coated with nickel for 68 min.

mum values at the surface layer and then a decrease towards stable values at the core [27–29].

Figure 6 shows Vickers indentation marks on a cross-section of an electroplated nickel coating with distinct variations in size, reflecting local differences in hardness due to microstructural changes throughout the thickness of the layer. The largest indentations were identified in the substrate region, indicating the lowest hardness values, which are generally associated with coarser grain sizes and residual stress relaxation within the nickel coating. This condition leads to reduced resistance to plastic deformation, as reported by Fattah and Morin [24] that an increase in grain size in electroplated layers directly contributes to a decrease in hardness.

Conversely, smaller indentation marks indicate higher hardness, reflecting a finer and more homogeneous microstructure. This is consistent with the findings of Thompson and Mahtabi [23] that fine-grained nickel layers exhibit higher hardness due to grain-refinement-based strengthening mechanisms in accordance with the Hall-Petch relationship. These variations in indentation size collectively support a transverse hardness profile indicating a microstructural gradient from the surface towards the interior of the layer.

CONCLUSIONS

Based on the results of the study, nickel coating through the electroplating method was proven to significantly improve the mechanical properties of the aluminum surface. Microstructural analysis showed that the thickness of the nickel coating increased with immersion time, from 3 μm at 17 min to 7 μm at 34 min, 11 μm at 51 min, and reaching 44 μm at 68 min. This growth of a thicker and denser layer directly contributes to an increase in material hardness. Before nickel plating, the aluminum specimens only had an average hardness of 69.44 HV, but after the electroplating process with variations in time of 17, 34, 51, and 68 min, the hardness increased successively to 118.32 HV, 191.32 HV, 258.40 HV, and 418.62 HV. This increase of up to 502% reflects the formation of a finer, denser, and more homogeneous nickel microstructure as the deposition duration increases. Thus, nickel electroplating has been proven to be effective in improving the hardness and mechanical quality of aluminum surfaces by increasing the thickness and density of the formed coating.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

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