

Article

Optimization of Nickel Coating Thickness on Copper via Ultrasonic-Assisted Electroplating

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ARTICLE INFO

Submitted 15 Jun 2026
Revised 29 Jun 2026
Accepted 30 Jun 2026
Published 30 Jun 2026



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Abstract.

This study provides a preliminary descriptive comparison of nickel coating thickness deposited on copper at a fixed current of 1.5 A and an electrolyte temperature of 45 °C for 60, 120, and 180 s, with and without assistance from a nominal 40 kHz ultrasonic bath. The Watts electrolyte contained nickel sulfate 300 g/L, nickel chloride 30 g/L, boric acid 30 g/L, brightener I 15 mL/L, and brightener II 1 mL/L. Based on the specimen dimensions shown in the experimental schematic and assuming that both broad faces were exposed, the nominal cathode area was approximately 29.82 cm² and the nominal current density was 5.03 A/dm²; this estimate excludes edge area and remains uncertain because masking and actual immersion were not documented. The reported local cross-sectional thickness increased from 4.76 to 8.27 μm without ultrasound and from 8.34 to 13.43 μm with ultrasonic-bath assistance as deposition time increased. Descriptive linear fits across the three time points gave R² values of 0.9995 and 0.9991, respectively. The ultrasonic-assisted values were 62.4–75.2% higher than the corresponding conventional values. Because the archived dataset contains one reported mean per condition based on repeated measurement locations rather than documented independent specimens, statistical significance, optimization, current efficiency, adhesion, uniformity, and overall coating quality are not claimed. The findings therefore constitute preliminary evidence that longer deposition time and ultrasonic-bath assistance were associated with higher locally measured nickel thickness under the reported conditions.

Keywords: nickel electrodeposition; copper substrate; ultrasonic bath; deposition time; coating thickness

INTRODUCTION

Electrodeposition is widely used to modify metallic surfaces because it enables the formation of controlled metal layers using relatively simple equipment, aqueous electrolytes, and direct-current power. The process is applied for corrosion protection, decorative finishing, dimensional restoration, and improvement of surface properties. Nickel is one of the most commonly deposited metals because it offers good corrosion resistance, hardness, and thermal stability [1], [2], [3], [4]. However, the resulting coating thickness and morphology are influenced by several electrochemical and process parameters, including current density, electrolyte composition, bath temperature, pH, electrode spacing, substrate preparation, agitation, and deposition time [5], [6].

During nickel electrodeposition, Ni^{2+} ions are transported from the electrolyte toward the cathode surface through migration, diffusion, and convection. When ion transport near the cathode is insufficient, a concentration boundary layer may develop and restrict the deposition rate [7]. This condition can also contribute to non-uniform growth and changes in surface morphology [8]. Therefore, improving electrolyte movement near the cathode is important for maintaining a more stable deposition process, particularly at relatively high current densities or during the early stages of coating formation.

Ultrasonic assistance has been introduced into electrodeposition to enhance mass transfer and modify interfacial conditions. Acoustic cavitation generates microscopic bubbles that repeatedly form, grow, and collapse in the liquid medium. The resulting microstreaming, pressure fluctuations, and localized microjets can disturb the diffusion layer, renew the electrolyte near the cathode, and promote the transport of nickel ions toward active deposition sites [9], [10]. These effects may increase the observed deposition rate and alter nucleation and coating growth. Nevertheless, the effectiveness of ultrasonic assistance depends on more than frequency alone. Ultrasonic power, bath geometry, liquid volume, specimen position, temperature, and exposure mode also influence cavitation intensity and process reproducibility.

Previous studies on nickel plating and ultrasonic-assisted electrodeposition have shown that bath composition, current density, agitation, and deposition time can affect coating thickness and morphology [11], [12], [13], [14]. In a Watts nickel bath, nickel sulfate supplies nickel ions, nickel chloride improves conductivity and supports anode dissolution, while boric acid functions as a pH buffer near the cathode. The addition of brighteners may further affect surface appearance and deposit growth. Under ultrasonic conditions, these chemical factors interact with cavitation-induced agitation, making it necessary to interpret the resulting coating response carefully.

An increase in coating thickness or a visually smoother SEM appearance should not automatically be interpreted as improved adhesion, lower porosity,

higher hardness, or better corrosion resistance. These properties require direct testing through adhesion, roughness, hardness, porosity, wear, or electrochemical measurements. Therefore, conclusions should remain limited to the responses that were actually evaluated.

The original experimental plan included currents of 0.5, 1.0, and 1.5 A. However, the archived dataset available for this manuscript contains complete paired thickness data only at 1.5 A. Accordingly, the study is not presented as a factorial optimization. Its scope is limited to comparing deposition times of 60, 120, and 180 s under conventional and ultrasonic-assisted conditions at a fixed current of 1.5 A and a nominal bath temperature of 45 °C. The objective is to evaluate the observed coating-thickness trend, compare the two deposition conditions, and identify parameters that should be controlled in future replicated experiments.

METHODS

Theoretical Basis and Study Scope

The theoretical nickel mass at 100% current efficiency follows Faraday's law, $m_{th} = ItM/(zF)$, where I is current, t is deposition time, M is the molar mass of nickel (58.6934 g/mol), $z = 2$ for Ni^{2+} reduction, and $F = 96,485$ C/mol. A corresponding mean thickness may be estimated from $h_{th} = m_{th}/(\rho A)$, where ρ is nickel density and A is the exposed cathode area [5], [11]. These relations require a verified active area. In the present archive, masking and the exact immersed area were not recorded; therefore, theoretical thickness is reported only as a nominal benchmark based on the geometry shown in Figure 1 and is not used to claim current efficiency.

Ultrasonic-bath assistance was applied at a nominal frequency of 40 kHz. The intended mechanism is cavitation-induced agitation and microstreaming, which may modify mass transport near the cathode [9], [10], [13]. The original record does not provide nominal ultrasonic power, bath capacity, power density, transducer arrangement, specimen-to-transducer distance, duty cycle, or ultrasound-induced temperature rise. Accordingly, the present analysis uses the neutral term “ultrasonic-bath assisted” and does not attribute the observed thickness difference to a quantified cavitation intensity.

Copper was used as the cathode substrate and nickel as the soluble anode. General material and surface-engineering information was taken from standard handbooks and technical references [15], [16], [17], [18], [19], [20]. The reported study did not measure substrate hardness, coating hardness, adhesion, porosity, roughness, corrosion resistance, or crystallographic structure; such properties are therefore outside the validation boundary.

Experimental Design and Apparatus

The revised analysis includes six conditions: three deposition times (60, 120, and 180 s) at a fixed current of 1.5 A and nominal electrolyte temperature

of 45 °C, each performed without ultrasonic assistance and with ultrasonic-bath assistance. The electroplating arrangement, electrode connections, and nominal specimen geometry used to interpret the exposed cathode area are shown in Figure 1. Because the original records do not document the immersed length, masking boundary, edge exposure, anode dimensions, electrode spacing, applied voltage, electrolyte volume, or anode-to-cathode area ratio, these parameters are reported as unavailable rather than reconstructed.

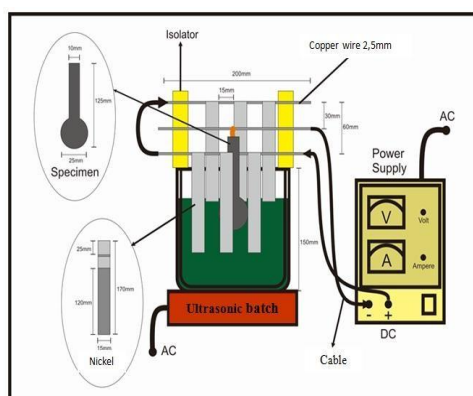


Figure 1. Schematic of the electroplating apparatus and nominal electrode geometry.

The drawing indicates a keyhole-shaped copper specimen with an overall length of 125 mm, a 10 mm-wide stem, and a 25 mm-diameter circular end; nickel anodes are shown as approximately 15 mm × 170 mm with 120 mm nominal immersed length. Dimensions are interpreted from the source schematic and are not a substitute for a verified masking and immersion record.

Electrolyte Composition

Table 1 lists the reported Watts nickel electrolyte composition. Concentrations are expressed per litre of electrolyte.

Table 1. Composition of the Watts nickel electrolyte solution.

Electrolyte Component	Concentration	Function
Nickel Sulfate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$)	300 g/L	Source of Ni^{2+} ions
Nickel Chloride ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$)	30 g/L	Enhances conductivity
Boric Acid (H_3BO_3)	30 g/L	pH buffer
Brightener I	15 mL/L	Surface leveling agent
Brightener II	1 mL/L	Brightening agent

Specimen Preparation and Electroplating Procedure

The copper specimen was mechanically and chemically cleaned before connection to the negative terminal of the adjustable DC power supply; the nickel anode was connected to the positive terminal. The schematic gives a nominal specimen area of 29.82 cm² (0.298 dm²) when both broad faces of the 125 mm keyhole geometry are included and edge area is neglected, corresponding to a nominal current density of 5.03 A/dm² at 1.5 A. Because the

archived record does not specify masking, actual immersed area, substrate thickness, anode purity, verified anode-to-cathode area ratio, applied voltage, electrolyte volume, bath pH, or the temperature-control method, the current-density value must be treated as an estimate. The drawing indicates an electrode spacing of approximately 55 mm. The record confirms mechanical and chemical cleaning but does not preserve abrasive grade, degreasing solution, acid-activation chemistry, rinsing sequence, or drying procedure. In the ultrasonic-assisted condition, the electrolyte container was placed in a nominal 40 kHz ultrasonic bath; power, bath capacity, power density, transducer position, exposure continuity, and temperature rise caused by ultrasound were not documented.

Thickness Measurement, SEM Observation, and Data Analysis

Coating thickness was assessed destructively from cross sections using optical microscopy with ImageRaster software and was visually checked using SEM. The available dataset provides one reported mean value for each condition, obtained from at least three measurement locations on the same reported coating. The number of independently prepared specimens was not recorded; the location readings therefore cannot be treated as independent experimental replicates. Standard deviations, confidence intervals, inferential tests, and error bars were not calculated. Linear regressions were fitted only to describe the three time points within each ultrasonic condition, and the resulting R^2 values are descriptive rather than evidence of a general kinetic law. The SEM archive did not retain exact current-time assignment, accelerating voltage, working distance, magnification metadata for every panel, or measurement location; consequently, SEM interpretation is restricted to qualitative visual differences and does not support claims of adhesion, porosity, roughness, or coating quality.

RESULT AND DISCUSSION

Descriptive Coating-Thickness Results

Table 2 presents the locally measured nickel-coating thickness at 1.5 A and 45 °C for the three reported deposition times. Each entry is a reported mean of repeated locations; independent specimen replication was not documented.

Table 2. Locally measured nickel-coating thickness at 1.5 A and 45 °C.

Current (A)	Temperature (°C)	Time (s)	Without US (μm)	With US (μm)
1.5	45	60	4.76	8.34
1.5	45	120	6.58	10.75
1.5	45	180	8.27	13.43

Relationship Between Deposition Time and Local Thickness

The measured thickness increased monotonically with deposition time under both conditions. Descriptive least-squares fits gave $h = 0.02925t + 3.0267$ ($R^2 = 0.9995$) without ultrasound and $h = 0.04242t + 5.7933$ ($R^2 = 0.9999$) with ultrasonic-bath assistance, where h is the locally measured thickness in micrometres and t is deposition time in seconds. These regressions describe only the three available time points and are not inferential kinetic models. The nominal Faradaic mass and thickness benchmarks used to contextualize the measurements are summarized in Table 3.

Table 3. Nominal Faradaic benchmark at 1.5 A based on the schematic cathode area.

Time (s)	Theoretical Ni mass (mg)	Nominal theoretical thickness (μm)	Without US (μm)	With US (μm)
60	27.37	1.03	4.76	8.34
120	54.75	2.06	6.58	10.75
180	82.12	3.09	8.27	13.43

The locally measured thicknesses exceed the nominal mean Faradaic thicknesses in Table 3. Apparent efficiencies calculated directly from these values would exceed 100%, which is physically inadmissible. This mismatch indicates that the inferred active area is not sufficiently reliable and/or that a local cross-sectional measurement is not representative of the whole cathode area. The present manuscript therefore does not report a current-efficiency value and identifies verified masking, mass gain, and area-averaged thickness as essential measurements for future work.

Observed Effect of Ultrasonic-Bath Assistance

At each time point, the ultrasonic-bath-assisted condition produced a higher observed local thickness than the conventional condition: 8.34 versus 4.76 μm at 60 s, 10.75 versus 6.58 μm at 120 s, and 13.43 versus 8.27 μm at 180 s. These differences correspond to observed increases of 75.2%, 63.4%, and 62.4%, respectively. Representative cross-sectional and surface SEM observations for both deposition conditions are presented in Figure 2. Because independent replication and ultrasonic power data are unavailable, the thickness differences are not described as statistically significant and cannot be attributed solely to cavitation intensity. They are consistent with the possibility that ultrasonic agitation altered local mass transport, but bath geometry, temperature variation, current distribution, masking, and measurement location remain potential contributors [9], [10], [13].

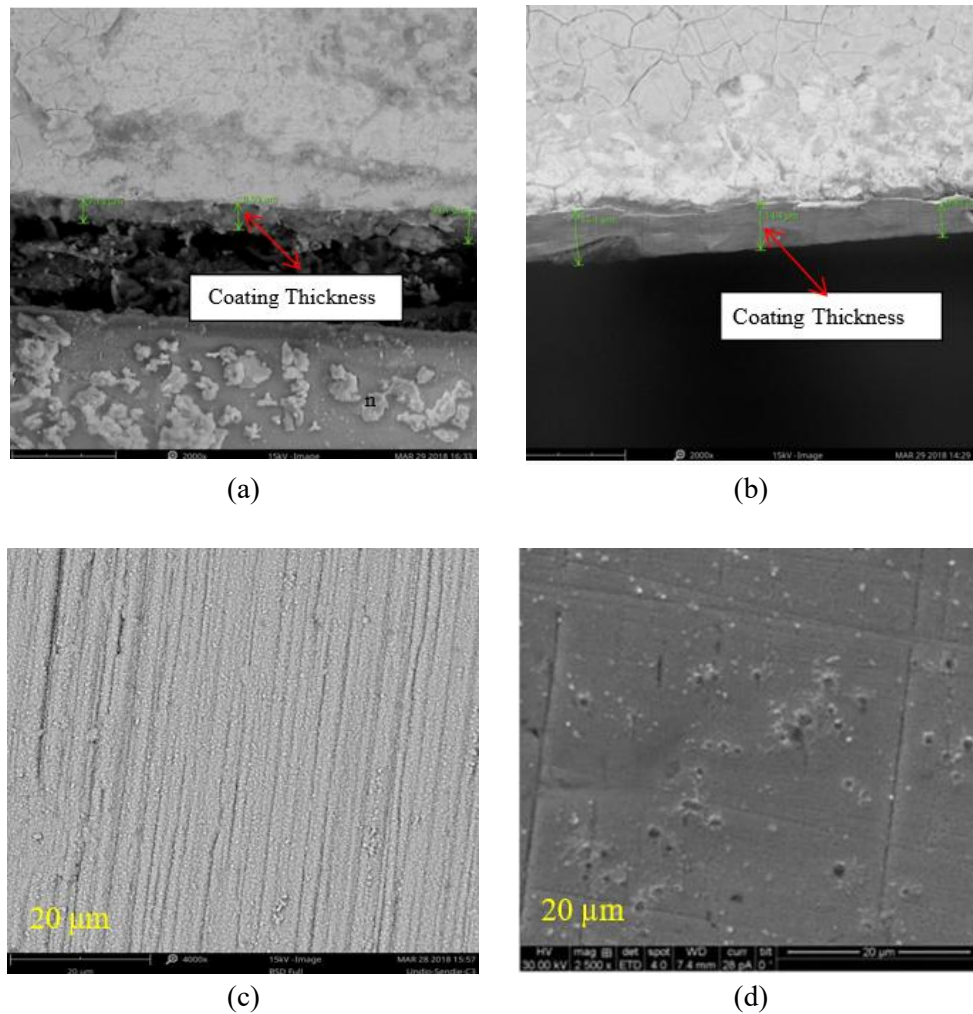


Figure 2. Representative SEM observations: (a) conventional cross section, (b) ultrasonic-bath-assisted cross section, (c) conventional surface, and (d) ultrasonic-bath-assisted surface. Original scale bars are retained. Exact current-time allocation and complete SEM acquisition metadata were not preserved in the available archive.

As shown in Figure 2, the cross-sectional panels identify locally measured coating boundaries, whereas the surface panels show visually different textures. The ultrasonic-assisted surface appears comparatively smoother in the supplied images. However, the images are not sufficient to quantify roughness, porosity, adhesion, or coating uniformity because equivalent magnification, accelerating voltage, acquisition location, and statistically representative fields were not documented. The SEM evidence is therefore interpreted only as qualitative morphology, consistent with published observations that ultrasonic agitation can modify electrodeposited nickel morphology without, by itself, proving improved functional performance [9], [13], [21].

Data Visualization

Figures 3–5 summarize complementary aspects of the reported thickness data. Figure 3 emphasizes the time-dependent trend and descriptive regression,

Figure 4 compares the absolute thickness values between deposition modes, and Figure 5 expresses the ultrasonic-associated difference relative to the conventional value at each time. Inferential error bars are not included because independently prepared specimen replicates were not documented.

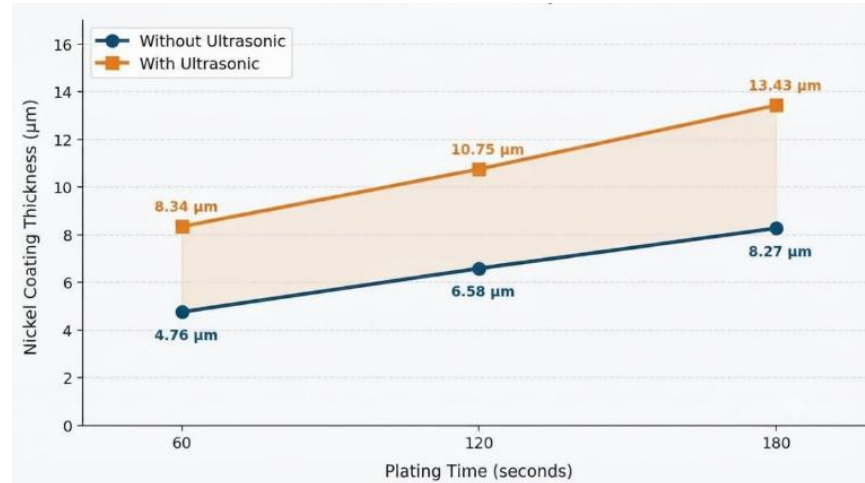


Figure 3. Local nickel-coating thickness versus deposition time at 1.5 A and 45 °C, with descriptive linear fits based on three time points per condition.

Figure 3 shows that the reported local thickness rose from 4.76 to 8.27 μm under conventional deposition and from 8.34 to 13.43 μm under ultrasonic-bath assistance as time increased from 60 to 180 s. The corresponding descriptive slopes, 0.02925 and 0.04242 $\mu\text{m/s}$, indicate a steeper observed thickness increase in the ultrasonic-assisted series within the tested interval. This direction is consistent with the charge–time relationship in Faraday’s law and with nickel-electrodeposition studies reporting that ultrasonic agitation can increase deposition rate by improving electrolyte renewal and mass transport near the cathode [9], [13]. Nevertheless, the high R^2 values are based on only three time points and should not be extrapolated beyond the present conditions.

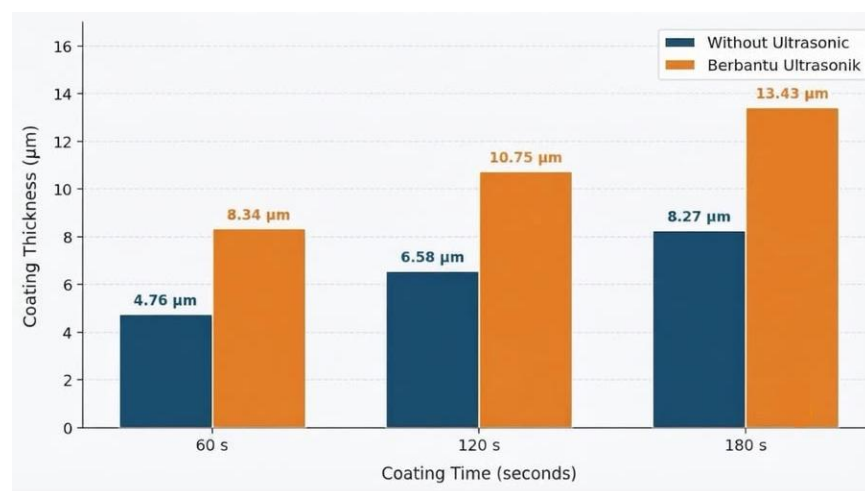


Figure 4. Comparison of reported local thickness values for conventional and ultrasonic-bath-assisted deposition.

Figure 4 highlights that the absolute difference between the two deposition modes increased from 3.58 μm at 60 s to 4.17 μm at 120 s and 5.16 μm at 180 s. Thus, although both conditions accumulated nickel with time, the ultrasonic-bath-assisted specimens retained a larger observed local thickness throughout the reported interval. A previous ultrasonic-bath electroplating study on copper and stainless-steel substrates likewise reported enhanced coating development under ultrasonic assistance [12], while other ultrasonic-assisted nickel studies have shown that agitation mode can alter transport conditions, deposit morphology, and electrochemical response [13], [21]. In the present work, however, the widening difference cannot be assigned uniquely to ultrasound because current distribution, actual exposed area, bath heating, and measurement location were not independently controlled or quantified.

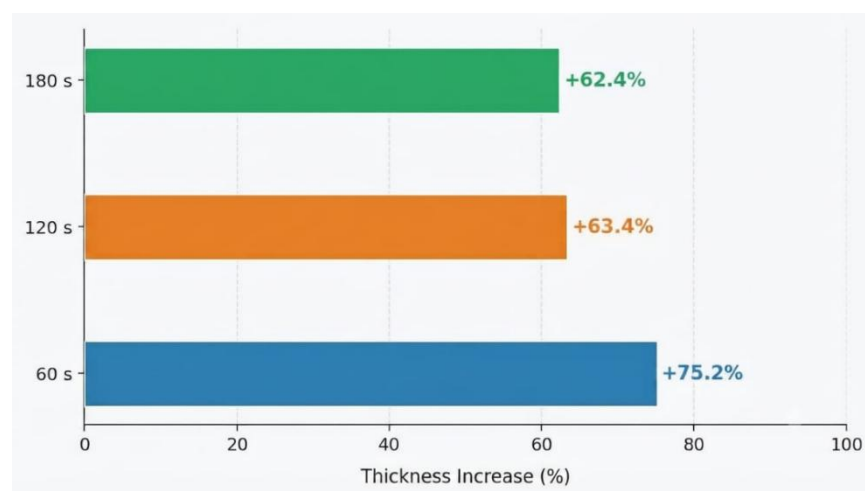


Figure 5. Observed percentage increase in local thickness for the ultrasonic-bath-assisted condition relative to the conventional condition at each deposition time.

Figure 5 shows that the relative thickness increase associated with ultrasonic assistance decreased from 75.2% at 60 s to 63.4% at 120 s and 62.4% at 180 s, even though the absolute thickness difference increased. This means that the proportional separation between the two series was greatest at the shortest deposition time, whereas the conventional series partly narrowed the relative gap as deposition proceeded. The pattern is compatible with the condition-dependent influence of cavitation and acoustic microstreaming on concentration-boundary-layer renewal reported in ultrasonic electrodeposition studies [9], [13], [21]. It does not demonstrate that cavitation intensity declined with time, because ultrasonic power, local acoustic field, and electrolyte temperature were not measured.

CONCLUSION

At a fixed current of 1.5 A and a nominal electrolyte temperature of 45 $^{\circ}\text{C}$, the reported local nickel-coating thickness increased monotonically as deposition time increased from 60 to 180 s. The conventional condition yielded

4.76, 6.58, and 8.27 μm , whereas the ultrasonic-bath-assisted condition yielded 8.34, 10.75, and 13.43 μm at 60, 120, and 180 s, respectively. Ultrasonic-bath assistance therefore produced higher observed local thickness at all three time points, corresponding to descriptive increases of 62.4–75.2% relative to the conventional condition; the largest absolute thickness was observed at 180 s with ultrasonic assistance. The available SEM images also indicate qualitative differences in surface texture, but the study does not establish statistical significance, verified current efficiency, improved adhesion, reduced porosity, greater uniformity, or superior coating quality because independently prepared replicates, complete ultrasonic operating parameters, verified masking and exposed area, and quantitative surface-property tests were unavailable. Future work should use separately prepared replicate specimens, measured current density and voltage, controlled pH and temperature, documented surface preparation and electrode geometry, calibrated ultrasonic power density, and quantitative roughness, porosity, adhesion, hardness, and corrosion testing so that deposition efficiency and coating performance can be assessed rigorously.

Acknowledgements

The authors gratefully acknowledge the Department of Mechanical Engineering, Politeknik Negeri Semarang, for providing laboratory facilities and technical support during the electroplating experiments and coating characterization. The authors also thank the Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, and the Department of Mechanical Engineering, Universitas Al Hikmah, for their academic support and contributions to the preparation of this manuscript.

REFERENCES

- [1] Ghina Imani Rofi and Maria Paristiowati, “The Effect of Electrodeposition Current and Electrolyte Composition on Electrodeposition of Fe-Ni Alloys,” *Chem. Mater.*, vol. 1, no. 2, pp. 55–60, 2022, doi: 10.56425/cma.v1i2.27.
- [2] P. Sebastián, V. Climent, J. M. Feliu, and E. Gómez, “Ionic Liquids in the Field of Metal Electrodeposition,” in *Encyclopedia of Interfacial Chemistry*, Elsevier, 2018, pp. 690–700. doi: 10.1016/B978-0-12-409547-2.13379-7.
- [3] D. Wang, F. Li, Y. Shi, M. Liu, B. Liu, and Q. Chang, “Optimization of the Preparation Parameters of High-Strength Nickel Layers by Electrodeposition on Mild Steel Substrates,” *Materials (Basel)*, vol. 14, no. 18, p. 5461, Sep. 2021, doi: 10.3390/ma14185461.
- [4] M. Próchniak and M. Grdeń, “Electrochemical deposition of nickel from aqueous electrolytic baths prepared by dissolution of metallic powder,” *J. Solid State Electrochem.*, vol. 26, no. 2, pp. 431–447, Feb. 2022, doi: 10.1007/s10008-021-05084-9.
- [5] S. S. Djokić, *Electrodeposition: Theory and Practice*. New York, NY, USA: Springer,

2010. doi: 10.1007/978-1-4419-5589-7.
- [6] H. Kuru, H. Kockar, M. Alper, and O. Karaagac, "Growth of Binary Ni--Fe Films: Characterisations at Low and High Potential Levels," *J. Magn. Magn. Mater.*, vol. 377, pp. 59–64, 2015, doi: 10.1016/j.jmmm.2014.10.047.
- [7] N. Ghiasi, P. Sharma, A. Jung, and S. Diebels, "Modelling the electrodeposition of nickel on polyurethane foam," *Arch. Appl. Mech.*, vol. 95, no. 11, p. 252, Nov. 2025, doi: 10.1007/s00419-025-02959-5.
- [8] M. Sahlman, J. Aromaa, and M. Lundström, "Effects of Ni and electrolyte additives on electrorefined Cu cathode surfaces," *Can. Metall. Q.*, vol. 65, no. 2, pp. 2050–2061, Apr. 2026, doi: 10.1080/00084433.2025.2515548.
- [9] K. A. Deepthi *et al.*, "Physical and Electrical Characteristics of NiFe Thin Films Using Ultrasonic-Assisted Pulse Electrodeposition," *Appl. Surf. Sci.*, vol. 360, pp. 519–524, 2016, doi: 10.1016/j.apsusc.2015.10.181.
- [10] T. J. Mason and J. P. Lorimer, *Applied Sonochemistry: The Uses of Power Ultrasound in Chemistry and Processing*. Weinheim, Germany: Wiley-VCH, 2002. doi: 10.1002/352760054X.
- [11] G. A. DiBari, *Nickel Plating Handbook*. Brussels, Belgium: Nickel Institute, 2014.
- [12] S. Y. Margen, S. Sulisty, S. Nugroho, and Y. Setiawan Adi Nugroho, "Enhancement Surface Coating Stainless Steel and Copper Using Ultrasonic Batch," *MATEC Web Conf.*, vol. 159, p. 2051, 2018, doi: 10.1051/mateconf/201815902051.
- [13] P. B. S. N. V Prasad, R. Vasudevan, S. K. Seshadri, and S. Ahila, "The Effect of Ultrasonic Vibration on Nickel Electrodeposition," *Mater. Lett.*, vol. 17, no. 6, pp. 357–359, 1993, doi: 10.1016/0167-577X(93)90125-H.
- [14] A. M. Rashidi and A. Amadeh, "The Effect of Current Density on the Grain Size of Electrodeposited Nanocrystalline Nickel Coatings," *Surf. Coatings Technol.*, vol. 202, no. 16, pp. 3772–3776, 2008, doi: 10.1016/j.surfcoat.2008.01.018.
- [15] ASM International, *{ASM Handbook}, Volume 5: Surface Engineering*. Materials Park, OH, USA: ASM International, 1994.
- [16] ASM International, *{ASM Handbook}, Volume 13A: Corrosion---Fundamentals, Testing, and Protection*. Materials Park, OH, USA: ASM International, 2003.
- [17] ASM International, *{ASM Handbook}, Volume 9: Metallography and Microstructures*. Materials Park, OH, USA: ASM International, 2004.
- [18] ASM International, *{ASM Handbook}, Volume 3: Alloy Phase Diagrams*. Materials Park, OH, USA: ASM International, 1990.
- [19] A. Harnanto, *Kimia 3*. Jakarta, Indonesia: Departemen Pendidikan Nasional, 2009.
- [20] M. Boniardi and A. Casaroli, *Coppers*. Milan, Italy: Gruppo Lucefin Research \& Development, 2014.
- [21] B. Li *et al.*, "Ultrasonic-Assisted Electrodeposition of Ni/Diamond Composite Coatings and Its Structure and Electrochemical Properties," *Ultrason. Sonochem.*, vol. 73, p. 105475, 2021, doi: 10.1016/j.ultsonch.2021.105475.