Jurnal Teknik Kimia

Vol. 29, No. 3, 2023, 129-141
e-ISSN: 2721-4885
DOI: https://doi.org/10.36706/jtk.v29i1.1565
Online at http://ejournal.ft.unsri.ac.id/index.php/jtk

The effect of electrolyte concentration and temperature at electroplating with copper on the plate thickness and corrosion rate of plated gray cast iron

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Abstract

This study aims to determine the effect of variations in electrolyte solution concentration and copper electroplating temperature on gray cast iron to achieve the desired copper layer thickness and reduce the corrosion rate of gray cast iron impeller pumps. A total of 30 test specimens made from gray cast iron were used, with dimensions conforming to the ASTM G31-72 standard for corrosion rate testing. The specimens were coated with copper electroplating using three different solutions: solution 1 (195 g/L copper sulfate, 45 g/L sulfuric acid), solution 2 (205 g/L copper sulfate, 50 g/L sulfuric acid), and solution 3 (215 g/L copper sulfate, 55 g/L sulfuric acid). Each solution was used with dipping temperatures of 30 – 34 °C, 40 – 44 °C, and 50 – 54 °C. After being coated with copper, the layer thickness was measured using a digital coating thickness gauge (F&NF type). The corrosion rate was then tested using the weight loss method, following the ASTM G31-72 standard, by immersing the specimens in seawater for 240 hours. The test results showed that the highest average thickness was achieved with solution 3 and a plating temperature of 50 – 54 °C, measuring 27.46 µm. The lowest average thickness was with solution 1 and a plating temperature of 30 – 34 °C, measuring 26.23 µm. The lowest corrosion rate was observed with solution 3 and a plating temperature of 50 – 54 °C, at 0.0041 mmpy, whereas the highest corrosion rate was found with solution 1 and a plating temperature of 30 – 34 °C, at 0.0079 mmpy. For comparison, the average corrosion rate of uncoated specimens was 2.2947 mmpy.

Keywords: gray cast iron, copper electroplating, concentration, corrosion rate, temperature.

How to Cite: Iksanudin, M., Widodo, R. D., Fitriyana, D. F., & Anggoro, A. B. (2023). The Effect of electrolyte concentration and temperature at electroplating with copper on the plate thickness and corrosion rate of plated gray cast iron. Jurnal Teknik Kimia, 29(3), 129-141. https://doi.org/10.36706/jtk.v29i3.1565

1. INTRODUCTION

The seawater cooling pump impeller made of gray cast iron experiences corrosion initiated by abrasive particles contained in the fluid, which strike the rotating impeller, causing abrasion (Jaelani, 2021). The damage to gray cast iron caused by corrosion elements shows a minimum form of localized corrosion (Abraham et al., 2022). The microstructure of gray cast iron contains graphite flakes in an iron matrix (Singh, 2020). The hardness value of gray cast iron is around 400 HV and can decrease if tempered from a temperature of 400 °C to 700 °C to 315 HV to 215 HV (Woodward et al., 2022). To reduce seawater corrosion damage, gray cast iron is

Received June 2023, Revised August 2023, Accepted for publication November 2023

given a protective Co (Ni) coating, which has a smaller impact on magnetic loss (Li et al., 2022). Metal coating methods, such as electroplating, can reduce the corrosion rate of metals (Prabowo et al., 2021). One of the corrosion-resistant coating materials is copper. Copper is a heavy metal that is ductile and malleable (Malhotra et al., 2020) and is one of the coating materials that has good anti-corrosion properties and hardness. The hardness of copper is approximately 369 MPa on the Vickers scale and 874 MPa on the Brinell scale (Iyasu et al., 2020).

The thickness of the copper electroplating layer and the reduction in corrosion rate are influenced by several parameters, including electrolyte solution concentration, current density, plating temperature, plating time, anode-cathode distance, and voltage (Yetri et al., 2020). Research on the electrolyte solution concentration and plating temperature on layer thickness (Sumpena and Wardoyo, 2021) has been conducted by several researchers, such as Pratiwi et al. (2020) on the effect of time and temperature variations in zinc electroplating on the thickness, adhesion strength, and corrosion resistance of steel. Dwiyati et al. (2022) on the effect of copper-nickel and copper-nickel-silicon electroplating on the corrosion rate of low carbon steel, Toifur et al. (2019) on the effect of plating temperature variations on copper layer thickness, Wahyudi et al. (2019) on the effect of copper concentration and current density on the morphology of copper electrodeposition deposits, Jaramillo-Gutiérrez et al. (2021) on the differences in electrolyte solution concentration on layer weight and thickness, Afriando (2018) on the time and temperature of copper electroplating solution on steel surface hardness and layer thickness, and Pamungkas et al. (2018) on the variations in electroplating temperature on layer thickness.

Research on the electrolyte solution concentration and plating temperature on the corrosion rate has been conducted by several researchers, such as Hardiyanti and Santoso (2018) on the variation of copper plating solution concentration on the corrosion rate of gray cast iron; Yusron et al. (2020) on the effect of time, distance, and plating temperature on the plating corrosion rate; Supriyatna et al. (2021) on the corrosion rate of electroplating using the weight loss method; and Syamsuir et al. (2019) on the corrosion rate of copper electroplating.

Research on electroplating to determine layer thickness and address the corrosion rate (Patty et al., 2019) is available, however research on the variation of electrolyte concentration and copper electroplating temperature on gray cast iron is still limited, especially to determine copper layer thickness and reduce seawater corrosion on gray cast iron. Therefore, research on electrolyte concentration and temperature is necessary, as they affect the copper plating thickness on gray cast iron. This study aims to determine the effect of electrolyte solution concentration and plating temperature on the thickness of the copper electroplating layer and the corrosion rate on gray cast iron.

2. MATERIALS AND METHODS

2.1 Preparation for Coating

The main material used is gray cast iron as the material to be coated and copper as the coating material. The gray cast iron to be coated was prepared according to the ASTM G31-72 standard (ASTM International, 2004), with specimen dimensions of 50 mm x 25 mm x 3 mm and a mounting diameter of 8 mm (Figure 1). The specimen surfaces were then smoothed with fine sandpaper to facilitate the electroplating process (Child, 1993). Next, the electrolyte solution was prepared according to the book "Electroplating: Basic Principles, Processes and Practice" (Kanani, 2004), where the standard concentration range for copper is 150-250 g/L copper (II) sulfate ($CuSO_4$) and 30-75 g/L sulfuric acid (H_2SO_4) in 1 liter of distilled water. The solutions used were solution 1 (195 g/L copper sulfate, 45 g/L sulfuric acid), solution 2 (205 g/L copper sulfate, 50 g/L sulfuric acid), and solution 3 (215 g/L copper sulfate, 55 g/L sulfuric acid), each dissolved in 1 liter of distilled water and stirred until the copper sulfate was completely dissolved. These variations were derived from a survey of several electroplating facilities in the field.

Then, the equipment and materials for the electroplating process were prepared, including copper plates, a rectifier, a stopwatch, a plastic tank, a thermometer, a ruler, and a water heater. The conditions for copper plating on gray cast iron were set as follows: the distance between the anode and cathode was 10 cm, the electrical voltage was 5 volts, and the current was 2 amperes.

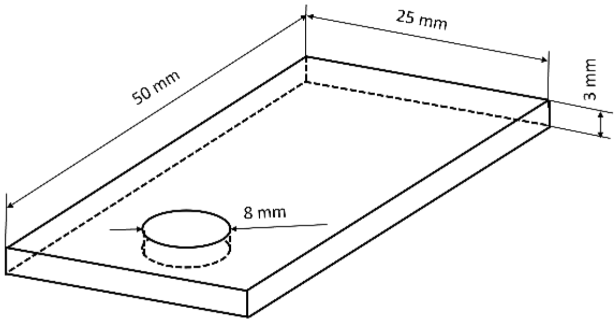

Figure 1. Dimension of Specimen

2.2 Specimen Coating

The specimen is manually cleaned; if it is rusty, it is soaked in 30 % HCl solution until the rust disappears, then washed with soapy water and rinsed with running water. It is scrubbed using a cloth or toothbrush until free from dirt and soap residue, ensuring no soapy film remains, as this could affect the final result. The coating process involves placing a copper plate on the positive pole (anode), attaching the specimen to the negative pole (cathode), and immersing it in an electrolyte solution. The rectifier is then activated, and the process occurs at a temperature of approximately 4 °C.

The initial coating process is conducted in Solution 1, starting at a heated temperature of 30 °C, followed by coating processes at 40 °C and then at 50 °C. The same sequence of coating processes is applied to Solution 2 and Solution 3, each starting at 30 °C, moving to 40 °C, and then to 50 °C. Each coating process for the different solutions and temperatures lasts for 10 minutes per batch of 3 specimens. After electroplating, specimens are dried and visually inspected.

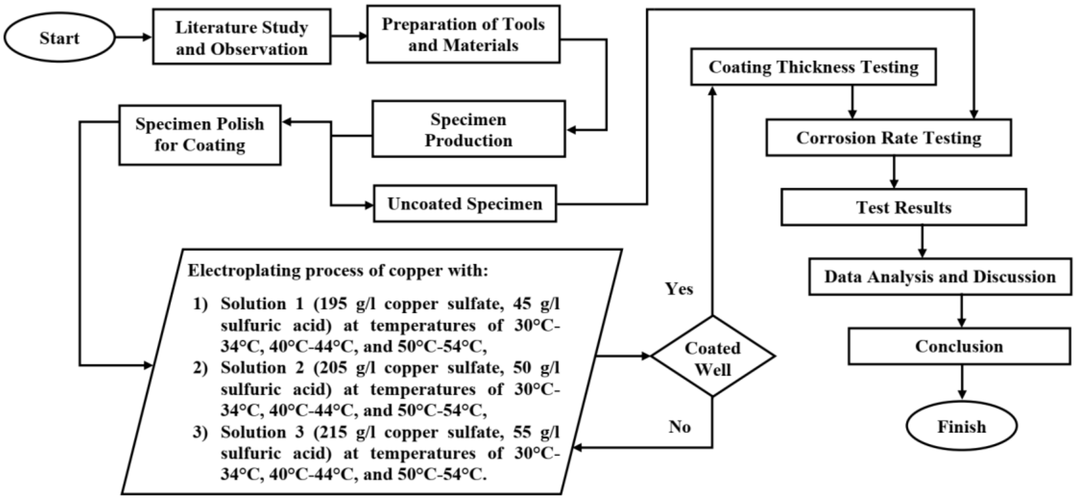

Figure 2. Research Flowchart

2.3 Specimen Testing

After copper plating is applied to gray cast iron specimens, the next step involves testing the coating's durability, specifically the thickness, using a digital coating thickness gauge (F&NF type) branded Graiger model CM-8856FN. It complies with ISO2178, ISO-2361, DIN, ASTM, and BS standards, with a measurement range of 01250 µm / 0~50 mil. The F probe is for non-magnetic materials, and the N probe measures non-magnetic coatings on non-magnetic metals. The gauge has a resolution of 0.1 µm (0~99.9 µm) or 1 µm, with an accuracy of 13 % n or 2.5 µm or 0.1 mil, operating at temperatures from 0~50 °C and humidity below 80 %. The thickness testing involves taking measurements at 6 points on each coated specimen, followed by averaging the values obtained.

Figure 3. Coating Thickness Tes

Specimens coated with copper and uncoated specimens undergo corrosion rate testing according to ASTM G31-72 standards. First, the specimens are weighed using an analytical balance to determine the initial weight. Subsequently, the specimens are immersed for 240 hours in seawater contained in a water bath. This immersion is conducted simultaneously in an open room, and records are kept of changes in temperature, pH, and parts per million (PPM) in the seawater during the specimen immersion. After the immersion period, the specimens are removed, cleaned, and dried. They are then briefly immersed in 30% HCl solution for approximately 15 seconds to remove scale and rust from the specimens, followed by rinsing with flowing water and drying.

Figure 4. Weighing of Specimens

After the specimens are dry and clean, they are weighed again using an analytical digital balance to determine the final weight of the specimens after immersion in the corrosive solution. The difference between the initial and final weights is then used in the corrosion rate formula according to ASTM G31-72 standards to determine the corrosion rate of both coated and uncoated specimens.

The standard ASTM G31-72 formula to determine the corrosion rate of the specimen is as follows Eq.1:

$$\text{Corrosion rate} = (K \times W) / (A \times T \times D) \quad (1)$$

K = a constant (see below)
T = time of exposure in hours to the nearest 0.01 h
A = area in cm2 to the nearest 0.01 cm2
W = mass loss in g, to nearest 1 mg
D = density in g/cm^3

To obtain the corrosion rate value, it is necessary to obtain the constants (K) data for mmpy, the area (A), and the immersion time (T) as obtained from ASTM G31-72 standard, as shown in Table 1.

Table 1. Corrosion Rate Constants, Time, and Specimen Area

Constant for mmpy	87.600
Time	240 *hours*
Area	29,8 cm^2 - 30,2 cm^2

Next, the copper density (DT) according to the standard in the book "Physical Properties of Copper" (Li & Zinkle, 2012) is required. Physical and mechanical properties of copper are tested, including tensile properties, fracture toughness, fatigue, creep-fatigue using the Materials Open Test Assembly (MOTA), and temperature tests as listed in Table 2.

Table 2. Physical properties of copper

Melting Point	1083 °C
Copper Density	8,95 g/cm^3
Thermal Conductivity	391 Wm/K
Elastic Modulus	117 GPa

Next, the density of gray cast iron (DB) is required according to ASTM A 48: Standard Specification for Gray Iron Castings (ASTM International, 2004), which is 7.15 g/cm³. The results of the coating thickness and corrosion rate tests are then presented in tables and graphs for analysis and drawing conclusions.

3. RESULTS AND DISCUSSION

3.1 Coating Thickness Testing

The results of the coating thickness testing yield thickness values in μm. The coating thickness varies among specimens due to differences in solution concentration and plating temperature. The coating thickness test results are presented in Figure 6 as a line graph showing the changes in copper coating thickness resulting from variations in electrolyte solution concentration and plating temperature. The test involved 9 specimens, with the following specimen codes: Solution 1 (195 g/l copper sulfate, 45 g/l sulfuric acid) had 3 specimens, namely 1.1, 1.2, 1.3; Solution 2 (205 g/l copper sulfate, 50 g/l sulfuric acid) had 3 specimens, namely 2.1, 2.2, 2.3; and Solution 3 (215 g/l copper sulfate, 55 g/l sulfuric acid) had 3 specimens, namely 3.1, 3.2, 3.3.

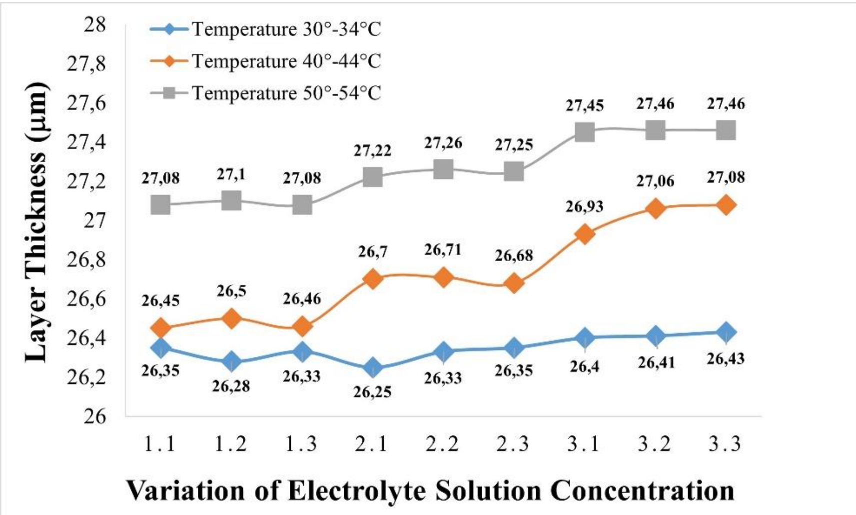

Figure 5. Thick Copper Layer with Variations in Concentration and Solution Temperature

The results were confirmed through testing using a digital coating thickness gauge (F&NF type) as recorded in Figures 5, which show an increase in the thickness values of the layers. The average thickness increase at temperatures of 30 – 34 °C was 26.23 μm for solution 1, which then increased to 26.47 μm for solution 2, and further to 27.09 μm for solution 3. At temperatures of 40 – 44 °C, the layer thickness started at an average of 26.31 µm for solution 1, increased to 26.70 µm for solution 2, and rose to 27.24 µm for solution 3. Finally, at temperatures of 50 – 54 °C, the average layer thickness began at 26.42 µm for solution 1, increased to 27.03 µm for solution 2, and rose to 27.46 µm for solution 3. These thickness testing results indicate an increase in layer thickness with increasing electrolyte solution concentration, consistent with previous research conducted by (Jaramillo et al., 2021) on nickel plating with variations in time, voltage, and nickel electrolyte solution concentration, similar to column 3 in Figure 6, where thickness increased with higher solution concentration.

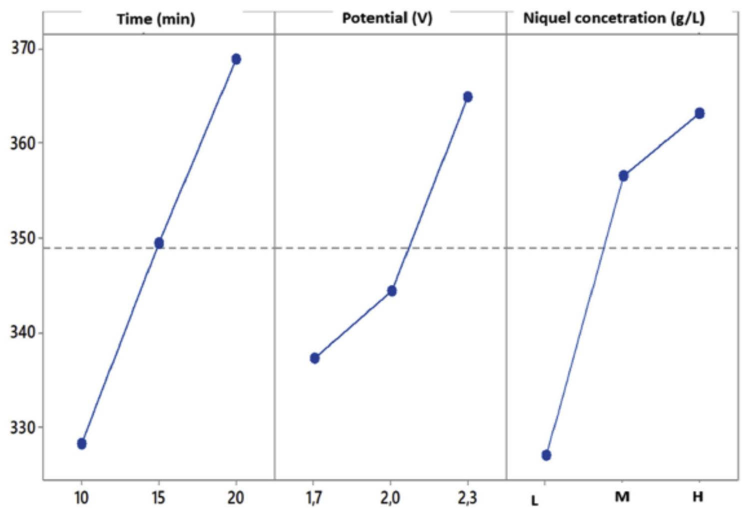

Figure 6. Thick Nickel Layer with Variations in Time, Voltage, and Solution Concentration

The results of the thickness testing also indicate an increase in layer thickness with rising deposition temperature. These findings are consistent with prior research conducted by (Toifur et al., 2018) on the microstructure, thickness, and resistivity of Cu/Ni layers with variations in the temperature of the electrolytic electroplating solution, concluding that higher temperatures lead to thicker Cu/Ni layers, as shown in Figure 7. Additionally, research by (Yetri, 2020) on the influence of time and temperature of the solution on the thickness and surface hardness of electroplated brass layers on steel shows that higher temperatures result in thicker brass layers, as detailed in Table 3.

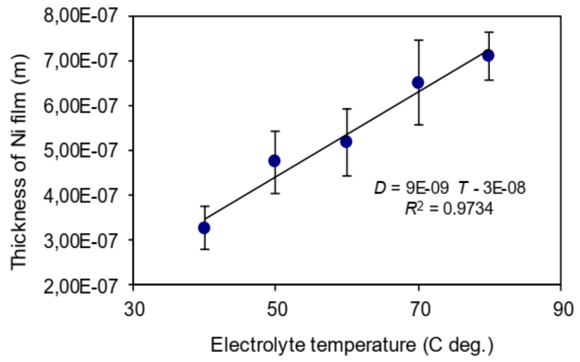

Figure 7. Thickness of Cu/Ni Layers with Variations in Electrolytic Solution Temperature

Table 3. Thickness of Cu/Ni Layers with Variations in Electrolytic Solution Temperature

Time (minutes)	Temperature (°C)			
	40	45	50	55
10	11,323	12,397	12,437	12,790
15	14,253	14,493	15,720	20,357
20	17,363	22,410	23,587	26,223
25	23,760	26,457	27,617	29,333

Based on the data obtained, the results of the layer thickness test show that the concentration of the solution and temperature in the copper electroplating process on gray cast iron affect the thickness of the layer on the specimen's surface. This is due to the equilibrium of the given concentration and the addition of temperature in the copper electroplating process resulting in different layer thicknesses.

3.2. Corrosion Rate Testing

Corrosion rate testing using the weight loss method according to ASTM G31-72 standard for specimens coated and uncoated with copper yielded corrosion rate values in mmpy (millimeters per year). The corrosion rate results can be viewed and analyzed in Figure 8, depicted as a line graph illustrating changes in copper layer corrosion rates due to variations in electrolyte concentration and deposition temperature on gray cast iron, with a total of 8 specimens categorized under Solution 1 (1.1, 1.2, 1.3), Solution 2 (2.1, 2.2, 2.3), and Solution 3 (3.1, 3.2, 3.3). Additionally, Figure 9 shows corrosion rates for uncoated gray cast iron specimens, symbolized by codes RAW 1, RAW 2, and RAW 3.

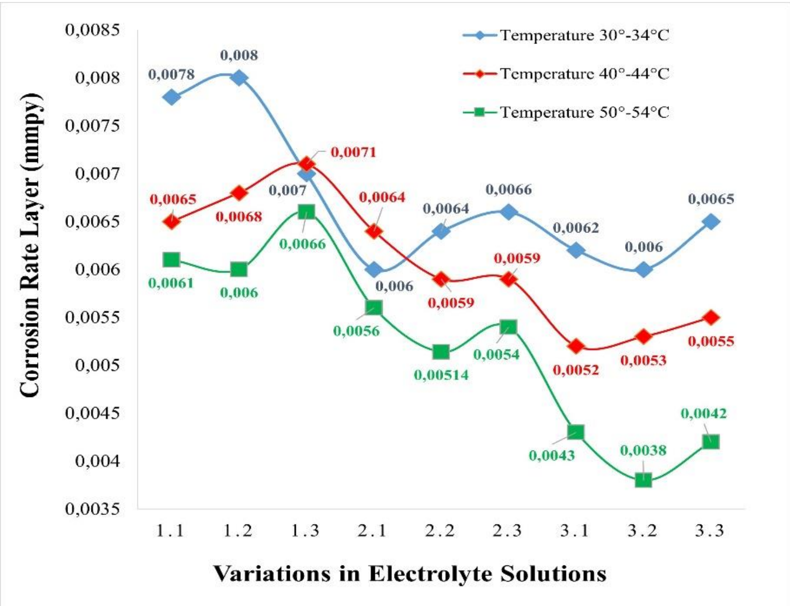

Figure 8. Copper Corrosion Rate with Variations in Solution and Temperature

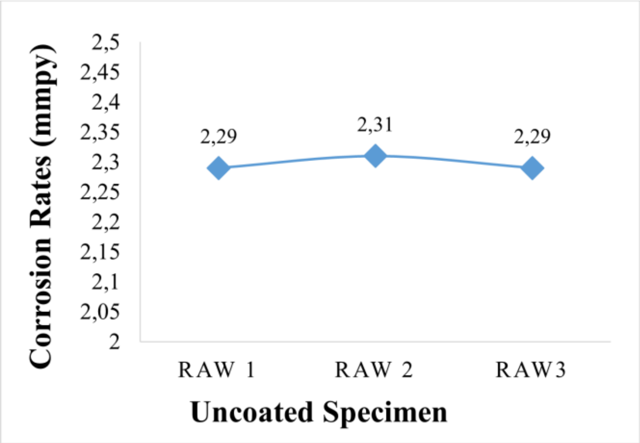

Figure 9. Corrosion Rate of Copper-Uncoated Specimens

The results of corrosion rate testing using ASTM G31-72 standards can be seen and corroborated by the graph in Figure 8, which illustrates the reduction in copper coating corrosion rate and how variations in deposition temperature affect the copper coating corrosion rate on gray cast iron. The average corrosion rate of untreated gray cast iron is 2.298836478 mmpy. Meanwhile, the average copper coating corrosion rate at temperatures of 30 – 34 °C is 0.007909257 mmpy for solution 1, then decreases to 0.006863082 mmpy for solution 2, and further decreases to 0.006278694 mmpy for solution 3. At temperatures of 40 – 44 °C, the coating corrosion rate starts at an average of 0.006447236 mmpy for solution 1, then decreases to 0.006135380 mmpy for solution 2, and reduces to 0.005417724 mmpy for solution 3. Finally, at temperatures of 50 – 54 °C, the average coating corrosion rate begins at 0.006286440 mmpy for solution 1, decreases to 0.005376860 mmpy for solution 2, and further decreases to 0.004133377 mmpy for solution 3. Figure 8 shows that the corrosion rate decreases with increasing deposition temperature. These findings align with previous research by (Yusron et al., 2020) on chrome plating on medium carbon steel with variations in solution temperature and anode-cathode distance, showing a decreasing corrosion rate with increasing solution temperature, as detailed in Table 4. Research by (Pratiwi et al., 2019) on the influence of zinc electroplating time and temperature variations on the thickness and corrosion rate of steel also indicates that as temperature increases, corrosion rate decreases, as shown in Table 5.

Table 4. Results of Electroplating Chrome Corrosion Rate Test at 3 cm Distance

Temperature (°C)	Electrode distance 3 cm	
	Icorr	CPR (mmpy)
55	281,111	$3{,}2665.10^{-4}$
	326,470	$3{,}7936.10^{-4}$
60	184,100	$2{,}1392.10^{-4}$
	185,980	$2{,}1611.10^{-4}$
65	17,0340	$1{,}9793.10^{-5}$
	29,1690	$2{,}1611.10^{-5}$
70	6,26180	$7{,}2761.10^{-6}$
	2,34110	$2{,}7203.10^{-6}$

Table 5. Results of Zinc Electroplating Corrosion Rate Testing

Temperatur (°C)	Waktu (menit)	*Weight loss* (gram)	Laju Korosi (mmpy)
25	9	0,0076	0,0206
	12	0,0064	0,0173
	15	0,0062	0,0168
30	9	0,0072	0,0195
	12	0,0060	0,0162
	15	0,0051	0,0138
35	9	0,0047	0,0127
	12	0,0038	0,0103
	15	0,0036	0,0097

The test results indicate that increasing the concentration of the electrolyte solution also reduces the corrosion rate for copper layers on gray cast iron. This finding aligns with previous research by (Hardiyanti and Santoso, 2018) on copper plating on gray cast iron using electrolyte mixtures with 30 %, 50 %, and 70 % $CuSO_4$ variations, studying their corrosion resistance. The results of this study can be seen in Figure 10.

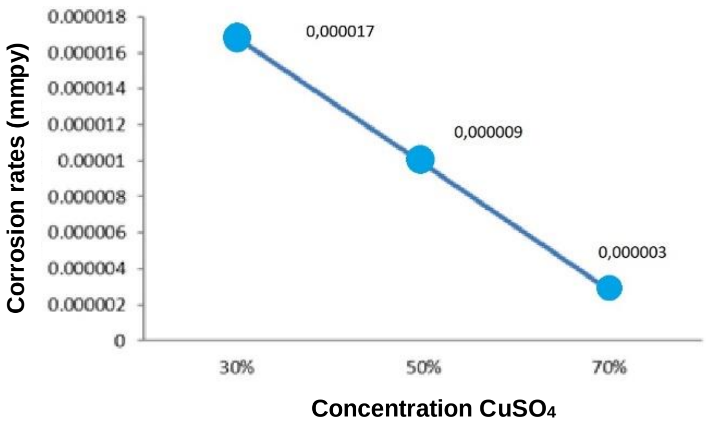

Figure 10. Copper Layer Corrosion Rate with CuSO4 Concentration Variations

For the average corrosion rate of uncoated materials, which is 2.29883647815495 mmpy, when compared to the corrosion rate of copper-coated materials as shown in Figures 8, 9, and 10, the difference in corrosion rates that can be reduced by electroplating copper ranges from 2.290927221 mmpy to 2.294703101 mmpy, or from 28,965.14 % to 55,516.43 %. The corrosion rate test results of specimens without coating and specimens coated with copper electroplating show that copper plating can inhibit corrosion rates caused by seawater, which is consistent with previous research by (Hardiyanti and Santoso, 2018) on copper coating tested using salt solutions or NaCl as depicted in Figure 11. Additionally, another study on electroplating to reduce corrosion rates due to seawater was conducted by (Kardiman and Fauji, 2021) on the influence of current strength and nickel electroplating time on the hardness and corrosion rate of steel caused by seawater, with research results indicating that electroplating can reduce corrosion rates of steel due to seawater, as shown in Figure 11.

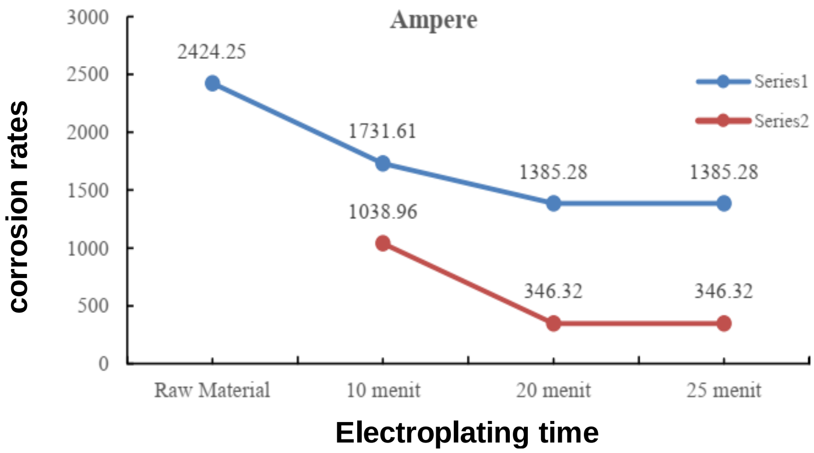

Figure 11. Graph of Reduction in Nickel Coating Corrosion Rate Due to Seawater

4. CONCLUSION

The concentration of electrolyte solution affects the thickness of copper electroplating layers on gray cast iron. The higher the concentration of copper sulfate and sulfuric acid used as electrolyte solutions, the thicker the copper layers become. The highest average thickness is found in solution 3. The highest average thickness is achieved at deposition temperatures of 50 – 54 °C, while the lowest average thickness is observed at deposition temperatures of 30 – 34 °C.

The concentration of the electrolyte solution also influences the reduction in corrosion rate of copper layers, where higher concentrations of copper sulfate and sulfuric acid in the electrolyte lead to a greater reduction in corrosion rate on the copper layers. Deposition temperature also plays a role in reducing corrosion, as higher deposition temperatures result in a lower corrosion rate.

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