Effect of Current Density, Surfactants, and $CuSO_4$ Concentration on Copper Electroplating of Iron Surfaces

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Abstract

Corrosion poses a serious threat to various industries, leading to financial burdens and infrastructure deterioration. This research investigates the influence of current density, surfactants, and $CuSO_4$ concentration on the electroplating process of copper onto iron surfaces. Current densities of 0.069825, 0.078069, 0.082062, 0.096939, and 0.129863 A in^{-2}, boric acid surfactant concentrations of 0.6, 0.9, 1.2, 1.5, and 1.8 g, and $CuSO_4$ concentrations of 0.40, 0.45, 0.50, 0.55, and 0.60 N were analyzed to assess their effects on the quality of the deposited copper layer. For each condition the deposited layer was evaluated through changes in specimen thickness and mass and through an extrapolated corrosion rate (mils per year, mpy) of the copper anode. Increasing current generally raised the amount of deposited copper, but the relationship with thickness, mass, and corrosion rate was non-monotonic rather than strictly increasing, indicating that current alone does not control coating quality. Adding boric acid buffer promoted a smoother deposit and, at the highest addition (1.8 g), coincided with the lowest measured anodic corrosion rate; excessive amounts, however, are undesirable on adhesion and toxicity grounds. Within the range tested, a moderate $CuSO_4$ concentration gave the most uniform deposition. Because corrosion rates were extrapolated to an annual basis from very short (5 min) tests, the absolute mpy values should be read as relative comparisons only. The results underline the need to tune, rather than simply maximise, electroplating parameters to obtain a high-quality copper coating on iron.

Keywords: Iron substrate; Copper electrodeposition; Current density; Boric acid buffer; Corrosion rate

1. Introduction

Corrosion of iron and steel is one of the most persistent and costly problems in modern industry, imposing enormous economic losses through material replacement, maintenance, and unexpected structural failure[1]. In humid, saline, and acidic environments, exposure to moisture, dissolved salts, and oxygen accelerates the oxidation of iron, producing rust and progressively weakening the mechanical integrity and service life of the affected components. Unprotected iron can corrode at rates exceeding 0.1 mm $year^{-1}$ in marine conditions and up to about 0.9 mm $year^{-1}$ in zones of severe, concentrated attack[2]. These rates are further intensified by salinity, dissolved oxygen, and industrial pollution, and corrosion is notably more aggressive near chemical plants and manufacturing facilities. Similar degradation has been reported across a wide range of ferrous alloys and exposure conditions, from stainless steels susceptible to stress-corrosion cracking to weathering and high-manganese steels in industrial marine environments[3]. Protecting iron-based structures such as bridges, pipelines, and ship hulls is therefore essential, and applying a protective metallic coating is one of the most widely used strategies to extend their service life.

Various surface coating techniques have been developed to improve the corrosion resistance and durability of metallic materials, including thermal spraying, chemical vapor deposition, physical vapor deposition, electroless plating, and electroplating[4]. Among the available coating techniques, electroplating (electrodeposition) is a simple, low-cost, and effective method for depositing a protective metal layer onto a metallic substrate [5]. In this process, a metal coating is formed on the substrate (the cathode) by passing a direct electric current through an electrolyte containing the coating-metal ions, causing those ions to be reduced and deposited on the substrate surface. Various metals, such as zinc, nickel, chromium, and copper, have been employed as coating materials in electroplating, each offering distinct advantages depending on the intended application and service environment [6]. Copper is a particularly attractive coating metal because of its good intrinsic corrosion resistance, excellent electrical and thermal conductivity, and ability to form a dense, adherent barrier layer on iron[7]. However, the quality of the deposited copper layer its thickness, uniformity, adhesion, and resulting corrosion resistance is highly sensitive to the operating conditions of the

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plating bath. Three of the most influential process parameters are the applied current density, the composition of the electrolyte, and the additives used to control deposit quality[8].

Current density is a critical parameter that governs the deposition rate, surface morphology, adhesion, and mechanical properties of the plated layer. Increasing the current density generally accelerates metal deposition and can raise coating thickness and hardness [9]. Beyond an optimal range, however, excessively high current densities promote rapid, uncontrolled deposition that produces rough, porous coatings with large, irregular grains and poor adhesion, making the layer more prone to corrosion. Studies on copper and copper-alloy electroplating consistently show that current density strongly affects both the deposit thickness and the corrosion behaviour of the coating, so that an intermediate, carefully controlled current density rather than the maximum attainable typically yields the best protective performance. Precise control of current density is therefore central to producing a durable copper coating[10].

In addition to the applied current, additives play an important role in refining the deposit. Surface-active agents can lower interfacial tension, improve deposit uniformity, and refine grain structure, and surfactants have been widely reviewed as anticorrosive additives that enhance coating morphology and corrosion resistance[11]. Besides surfactants, a variety of other additives are incorporated into electroplating baths to regulate electrolyte chemistry, improve deposit characteristics, and enhance process stability. These additives include pH buffers, brighteners, levelling agents, grain refiners, and stress-relieving agents, each serving a distinct function during electrodeposition. mong the buffering additives, boric acid (H_3BO_3) is one of the most widely used components in electroplating baths[12]. By stabilising the local pH at the cathode surface, boric acid suppresses hydrogen evolution and the associated gas-bubble entrapment, thereby reducing pitting and roughness and promoting a smoother, more uniform deposit[13]. Because boric acid functions mainly through pH buffering, it is treated in this study as a buffering additive rather than a surfactant. Its concentration is nonetheless kept low, as boric acid is toxic to humans and the environment.

The composition of the electrolyte is the third key factor. The electrolyte supplies the metal ions required for deposition, and its concentration directly influences the microstructure, thickness, and mechanical strength of the plated layer; variations in ion concentration alter grain size and porosity and, consequently, coating performance[14]. A wide range of electrolytes has been developed for electroplating, with the specific formulation depending on the coating metal and the desired deposit characteristics. For copper electroplating, copper sulfate ($CuSO_4$)-based electrolytes are the most commonly employed because they provide a stable source of Cu^{2+} ions, exhibit high electrical conductivity, and enable efficient deposition[15]. An electrolyte that is too dilute tends to yield thin, uneven coverage, whereas an excessively concentrated bath can promote rougher, defect-prone deposits; an optimal concentration is therefore needed to balance deposition rate against coating uniformity and corrosion resistance.

Although the individual effects of current density, additives, and electrolyte concentration have each been studied extensively, their combined and comparative influence on copper deposition onto iron within a single, consistent experimental framework is less frequently reported. Accordingly, this study investigates how three independent variables (i) the applied current / current density, (ii) the amount of boric acid added as a pH buffer, and (iii) the $CuSO_4$ electrolyte concentration affect the quality of copper electroplated onto an iron substrate. For each variable, the deposit is evaluated in terms of the change in specimen thickness, the change in specimen mass, and an extrapolated corrosion rate of the copper anode. It is hypothesised that each parameter exhibits an optimal, intermediate value rather than a simple "more-is-better" relationship, such that a high-quality copper coating is achieved by tuning, rather than maximising, each electroplating parameter.

2. Method

2.1. Materials and Substrate Preparation

The electroplating process of Fe metal with Cu coating was investigated under different conditions by varying current density, the addition of boric acid surfactant, and the electrolyte concentration. The electrolyte was copper(II) sulfate ($CuSO_4$) solution, and boric acid (H_3BO_3) was used as a pH-buffering additive. Prior to plating, each specimen was first mechanically abraded with abrasive paper to remove the surface oxide layer and other contaminants, and then acid-pickled in hydrochloric acid (HCl) solution to dissolve residual rust and oxide scale and to activate the metal surface. This combined mechanical and chemical pre-treatment improves surface cleanliness, coating adhesion, and reproducibility of the deposit. After pickling, the specimens were rinsed and dried. The length, width, and thickness of

every specimen were measured with a ruler and a micrometer screw gauge, and the mass was recorded on an analytical balance, before and after each experiment.

2.2. Electroplating Procedure

The Fe cathode was fixed to the black (negative) clamp and the Cu anode to the red (positive) clamp of the electroplating rig, and both electrodes were immersed in a beaker containing the $CuSO_4$ electrolyte for the relevant experiment. Three variables were studied one at a time, holding the others fixed. For the current-density series, plating was carried out at applied currents of 0.17, 0.19, 0.21, 0.23, and 0.25 A. For the buffer series, boric acid was added at 0.6, 0.9, 1.2, 1.5, and 1.8 g. For the electrolyte series, the $CuSO_4$ concentration was varied at 0.40, 0.45, 0.50, 0.55, and 0.60 N. After plating, specimens were removed, rinsed, dried, and re-weighed to determine the mass change. Each experiment is repeated under different parameter conditions to analyze the impact of current density, surfactant addition, and electrolyte concentration on the electroplating process. The collected data will be used to evaluate the effectiveness of the copper coating on the Fe substrate.

2.3. Corrosion-Rate Calculation

The corrosion rate of the metal was estimated from the mass change using the standard mils-per-year (mpy) relationship:

$$m_{py} = \frac{534 \times W}{D \times A \times T}$$

where W is the mass loss (mg), D is the density of copper (8.96 g cm^{-3}), A is the exposed area (in^2), and T is the exposure time (h).

3. Results and Discussion

3.1. Effect of Current Density on Electroplating Fe with Cu

The purpose of this experiment is to determine the effect of current density on Cu metal electroplating on Fe. Current density is the amount of electric current used in the electroplating process. While electroplating is a method of coating one metal with another metal through the electrolysis process. The amount of current density can affect the speed of metal deposition, the thickness of the layer and the quality of the final result on the metal[16], so this experiment aims to determine the effect of variations in current density in the Cu electroplating process can affect the layer deposited on Fe metal. The experiment began by preparing 5 samples of Fe and Cu metal. Furthermore, the metal surface was sanded to clean the surface and increase corrosion resistance. Furthermore, the length, width, and thickness of each iron were measured using a ruler and micrometer screw measuring tool so that the results were obtained according to Table 1. and the conditions were seen as follows:

Table 1. Dimensions of Fe and Cu Metals Before and After Electroplating

Metals	Before				After			
	Long (cm)	Width (cm)	Height (cm)	Weight (gr)	Long (cm)	Width (cm)	Height (cm)	Weight (gr)
Cu	3.9	2	0.087	4.35	3.9	1.9	0.069	4.4
	3.9	1.9	0.085	4.27	3.9	1.9	0.068	4.31
	3.9	1.9	0.086	4.35	3.9	1.9	0.068	4.4
	3.9	1.9	0.087	4.33	3.9	1.9	0.07	4.36
	4	1.9	0.084	4.32	3.8	1.9	0.07	4.39
Fe	4	1.9	0.058	2.7	3.8	1.9	0.086	2.69
	4	1.9	0.058	2.83	3.8	1.9	0.085	2.79
	4	2	0.067	2.94	3.8	2	0.085	2.9
	4	1.9	0.068	2.85	3.9	1.9	0.084	2.83
	4	2	0.056	2.97	3.8	2	0.084	2.92

Next, the cathode (Fe) is mounted on a black clamp, while the anode (Cu) is mounted on a red clamp, both connected to the electroplating tool. Then, both metals are inserted into a beaker glass containing a 0.5 N $CuSO_4$ solution. The electroplating process begins by waiting for the metal to be immersed in the solution for a period of 10 minutes with a current voltage of 0.17 A. After the electroplating process is complete, the metal is removed from the $CuSO_4$ solution and allowed to dry. The final weight of each metal is then measured to determine the electroplating results. This process is repeated for various current voltage variables of 0.19, 0.21, 0.23, 0.25 A so that the following conditions are produced. The visual appearance of the electroplated specimens obtained under the different current conditions is presented in Figure 1.

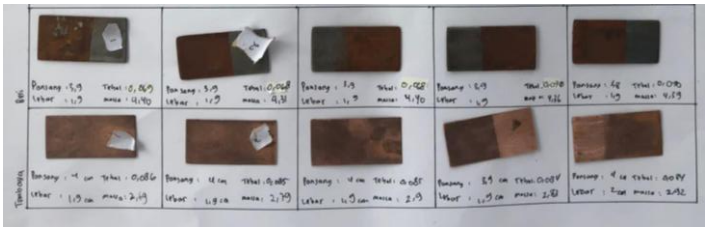

Figure 1. Metal Condition after Electroplating

After that, the difference in metal weight after the electroplating process can be measured to determine the corrosion rate that occurs. From the metal dimension data in Table 2, the surface area and weight difference were obtained, which were then used to calculate the corrosion rate.

Table 2. Corrosion Rate Calculation Results of Cu Metal

Metal	Δ Weight (mg)	Density (g/cm^3)	A (in^2)	T (hours)	MpY	Voltage (A)	Current Density (A/In^2)
1	10		2.434647		1468.752	0.17	0.069825
2	40		2.433733		5877.216	0.19	0.078069
3	40	8.96	2.55905	0.166667	5589.407	0.21	0.082062
4	20		2.372616		3014.304	0.23	0.096939
5	50		1.9251		9287.551	0.25	0.129863

Based on the corrosion rate calculation results presented in Table 2, the relationship between current density and the thickness variation of the electroplated Fe specimens is illustrated in Figure 2.

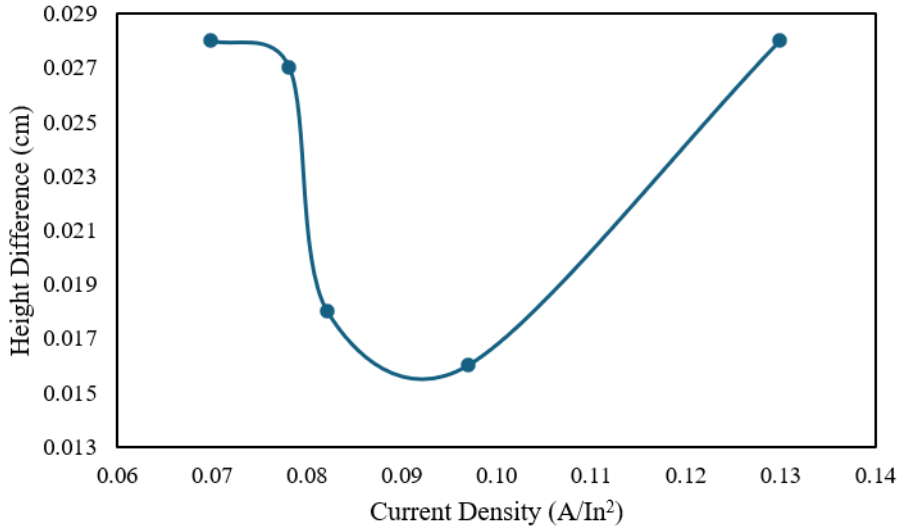

Figure 2. Effect of Current Density on Fe Metal Thickness Variation

As shown in Figure 2, the thickness variation of the electrodeposited specimens exhibits a non-linear relationship with current density. The thickness variation initially decreases as the current density increases, reaching a minimum at 0.082–0.097 A in^{-2}, before increasing again at higher current densities. This U-shaped trend suggests the

existence of an optimum current-density range for producing a more uniform deposit. According to Faraday's law of electrolysis, the amount of metal deposited is proportional to the electrical charge passed through the electrolyte, indicating that higher current densities generally increase the deposition rate[17]. However, deposition rate alone does not determine coating quality. The microstructure, compactness, and uniformity of the deposited layer are strongly influenced by the electrochemical kinetics of the electrodeposition process, resulting in an optimum current-density range that produces the most uniform coating[18].

At low current densities (0.070–0.078 A in^{-2}), the reduction of Cu^{2+} ions and the nucleation of new crystallites occur relatively slowly. Consequently, fewer nucleation sites are formed, allowing individual grains to grow larger before neighbouring nuclei develop. This condition generally produces coarse, non-uniform deposits with incomplete surface coverage, thereby increasing the measured thickness variation[19]. As the current density increases to the intermediate range (0.082–0.097 A in^{-2}), the nucleation rate becomes sufficiently high to promote the formation of numerous fine grains that grow uniformly across the substrate surface. The resulting coating is typically denser, more homogeneous, and better adhered to the substrate[20], which explains the minimum thickness variation observed in Figure 2. Similar behaviour has been widely reported for electrodeposited coatings, where intermediate current densities provide the best balance between deposition rate and coating quality[21].

When the current density exceeds 0.097 A in^{-2}, the thickness variation increases again. At these conditions, the electrochemical reaction approaches the limiting current density, causing Cu^{2+} ions to be consumed at the cathode faster than they can be replenished by diffusion from the bulk electrolyte. The resulting concentration polarization promotes uneven crystal growth, leading to rough, porous, and dendritic deposits[22]. Simultaneously, hydrogen evolution becomes increasingly significant, reducing the cathodic current efficiency and generating micro-voids or defects within the deposited layer. These structural imperfections decrease coating uniformity and contribute to the larger thickness variation measured at high current densities. Overall, the results indicate that an intermediate current density 0.082–0.097 A in^{-2} provides the most favorable deposition condition for the present electroplating system, yielding the smallest thickness variation and, consequently, the most uniform coating. At lower current densities, insufficient nucleation limits coating uniformity, whereas excessive current densities promote concentration polarization and hydrogen evolution, resulting in porous and defective deposits.

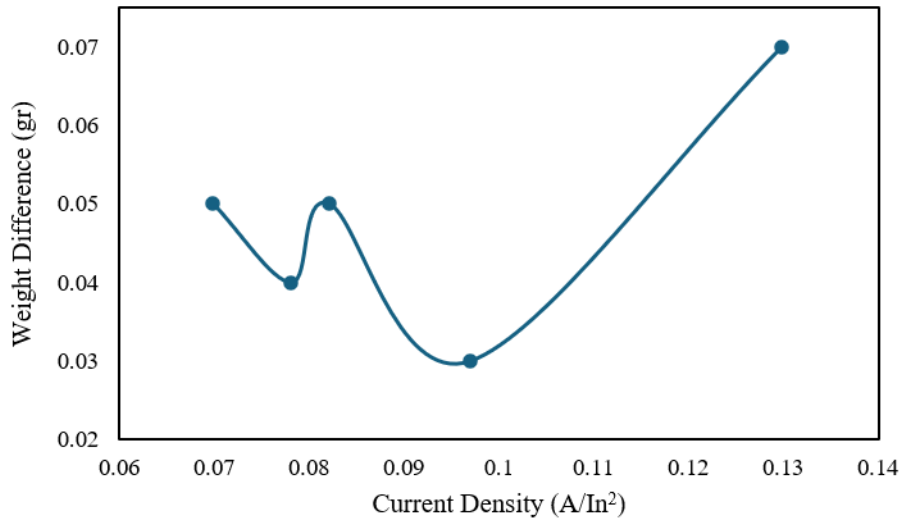

Figure 3. Effect of Current Density on Fe Metal Weight Difference

Based on Figure 3, the weight difference of the Fe specimens exhibits a non-linear relationship with the applied current density. The weight difference decreases with increasing current density, reaches a minimum at 0.097 A in^{-2}, and then increases again at higher current densities. This trend closely resembles the thickness variation presented in Figure 2, indicating that coating integrity strongly influences the corrosion-related weight change of the specimens [23]. The minimum weight difference observed at 0.097 A in^{-2} suggests that the deposited copper coating provided the most effective protection against corrosion. A lower weight difference indicates a smaller corrosion-related mass

change, which is generally associated with a denser and more uniform coating. Similar findings have been reported by Song et al. [24]and Tan et al. [25], who showed that compact electrodeposited coatings with reduced porosity exhibit improved corrosion resistance. At current densities above 0.097 A in^{-2}, the weight difference increases again, indicating a deterioration in coating performance. As discussed in the previous section Figure 2, excessive current density promotes concentration polarization and hydrogen evolution, resulting in a more porous and defective deposit that allows corrosion to occur more readily[26]. Consequently, the corrosion-related mass change becomes greater, leading to the higher weight difference observed at the highest current densities. Overall, the results confirm that an applied current density of 0.097 A in^{-2} provides the optimum electrodeposition condition for minimizing corrosion-related weight change, consistent with the thickness variation results presented in Figure 2.

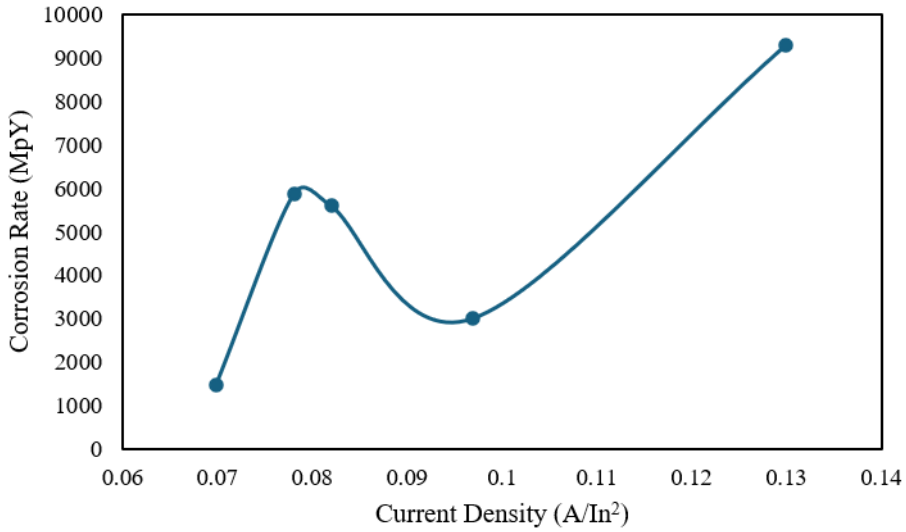

Figure 4. Correlation Between Current Density and Cu Corrosion Rate

In Figure 4 is a graph of the relationship between current density and Cu corrosion rate. Where from the graph can be seen the electroplating efficiency data at various levels of current density. At a current density of 0.06 A/in^2, the value reaches 1468.752085 mpy which shows how efficient the electroplating process is at relatively low current levels. Increasing the current density to 0.07 A/in^2 caused a significant spike reaching 5877.215934 mpy, signaling a drastic increase in Cu metal deposition on Fe metal. However, a decrease was observed at a current density of 0.08 A/in^2 of 5589.406783 mpy indicating other factors affecting the electroplating results. At a current density of 0.09, the value reaches 3014 mpy, indicating further fluctuations in the performance of the electroplating process. These fluctuations continue at a current density of 0.129 reaching 9287 mpy resulting in complex variations in electroplating efficiency as current density increases. This is in accordance with electrochemical theory which states that increasing current density can increase the corrosion rate because electric current can accelerate electrochemical reactions that cause metal corrosion[27]. However, there are fluctuations at current densities of 0.08 to 0.12 A/in^2 because changes in environmental parameters, such as temperature, humidity, or the concentration of certain chemicals in the environment, can significantly affect the corrosion rate. Fluctuations in environmental conditions can create variations in the response of metals to corrosion.

When interpreting the calculated corrosion-rate values, it is essential to recognise that these values represent the dissolution of the copper anode, which is intentionally consumed to generate Cu^{2+} ions during the electroplating process, rather than the corrosion behaviour of the iron substrate that the coating is designed to protect [26]. Consequently, these two phenomena should not be interpreted interchangeably. A relatively high corrosion rate of the copper anode reflects the intended electrochemical operation of the plating system and should not be regarded as evidence of poor material performance. Furthermore, the magnitude of the calculated corrosion rates, which reaches the order of thousands of mils per year (mpy), is primarily attributable to the experimental conditions rather than to exceptionally severe corrosion. The electroplating experiments were conducted using small specimens with exposed surface areas of 1.9–2.6 in^2, short plating durations of only 5 min, and single measurements without experimental

replication. Since the standard corrosion-rate equation expresses material loss on an annual basis, extrapolation from such short exposure times substantially amplifies the calculated values, resulting in corrosion rates that are considerably higher than the 40 mpy commonly reported for iron exposed to aggressive marine environments. Therefore, the previous interpretation that corrosion rates exceeding 200 mpy necessarily indicate poor corrosion resistance is not applicable in the present study. Such classification criteria are intended for evaluating the degradation of structural materials under service conditions rather than the intentional dissolution of a sacrificial copper anode during electroplating.

3.2. Effect of Electrolyte Concentration on Fe Electroplating with Cu

In this study, the dimensions of the Cu and Fe samples were measured before and after the electroplating process based on the electrolyte concentration change variable as in Table 3.

Table 3. Dimensions of Fe and Cu Metals Before and After Electroplating

Metals	Before				After			
	Long (cm)	Width (cm)	Height (cm)	Weight (gr)	Long (cm)	Width (cm)	Height (cm)	Weight (gr)
Fe	4.1	2	0.06	4.5	4	1.5	0.064	4.59
	4.1	2	0.057	4.41	4.1	1.9	0.062	4.44
	4.1	2	0.06	4.5	4	1.9	0.05	4.5
	4	2	0.055	4.4	4	1.9	0.06	4.47
	4	1.9	0.056	4.43	4	1.9	0.067	4.43
Cu	4	2	0.031	2.97	4	2	0.08	2.95
	4.1	2.1	0.03	3	4	2	0.082	2.98
	4	1.9	0.027	2.82	4	1.8	0.082	2.75
	4	2	0.028	2.99	4.1	2	0.08	2.96
	4.1	2	0.028	3	4	2	0.082	2.97

Figure 5. Metal Condition after Electroplating

Figure 5. shows the Fe metal and Cu metal after the electroplating process. The results of measuring the metal dimensions after the electroplating process are, in Fe metal, the length of Fe metal is 4 cm; 4.1 cm; 4 cm; 4 cm; and 4.1 cm, then the width of Fe metal is 2 cm; 2.1 cm; 1.9 cm; 2 cm; and 2 cm, the thickness of Fe metal is 0.031 cm; 0.03 cm; 0.027 cm, 0.028 cm, and 0.0.028 cm, respectively, and the mass of Fe metal is 2.95 gr; 2.98 gr; 2.75 gr; 2.96 gr; and 2.96 gr, respectively. Then the length of Cu metal is 4 cm; 4 cm; 4 cm; 4.1 cm; and 4 cm, then the width of Cu metal is 2 cm; 2 cm; 1.8 cm; 2 cm; and 2 cm, the thickness of Cu metal is 0.08 cm; 0.082 cm; 0.082 cm, 0.08 cm, and 0.082 cm, and the mass of Cu metal is 2.97 gr; 3 gr; 2.82 gr; 2.99 gr; and 3 gr, respectively. Based on the experiment, the part that is not protected by pilox is covered by rust and there is no significant change in the Cu metal. The electroplating process involves the flow of direct electric current through a circuit consisting of an anode, electrolyte solution, and cathode (workpiece). When direct current flows between the anode and cathode electrodes in the electrolyte solution, positive ionic charges are attracted to the cathode electrode. Conversely, negatively charged ions

move towards the positively charged electrode. These ions are neutralized by the two electrodes and the resulting solution is deposited on the cathode electrode.

Table 4. Corrosion Rate Calculation Results of Cu Metal

Metal	Δ Weight (mg)	Density (g/cm^3)	A (in^2)	T (hours)	MpY	Concentration (N)
1	20		2.6288		2720.551	0.4
2	20		2.63252		2716.707	0.45
3	70	8.96	2.37943	0.166667	10519.82	0.5
4	30		2.69328		3983.128	0.55
5	40		2.63252		5433.414	0.6

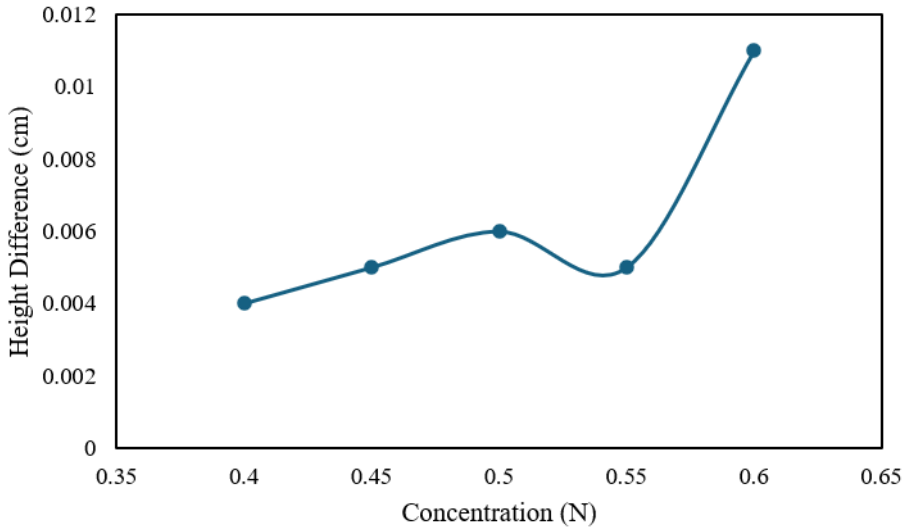

Figure 6. Effect of Concentration on Fe Metal Thickness Variation

Figure 6 shows the height (thickness) difference of the Fe specimens as a function of the $CuSO_4$ electrolyte concentration over the range of 0.40–0.60 N, while all other electroplating parameters (current, voltage, temperature, and plating time of 5 min) were kept constant. Under these conditions, electrolyte concentration was the only independent variable. The measured coating thickness differences were 0.004, 0.005, 0.006, 0.005, and 0.011 cm at $CuSO_4$ concentrations of 0.40, 0.45, 0.50, 0.55, and 0.60 N, respectively. Overall, the coating thickness increased with increasing electrolyte concentration, although a slight decrease was observed at 0.55 N before a pronounced increase at 0.60 N. The observed increase in coating thickness is consistent with the fundamental role of electrolyte concentration in electrodeposition. Increasing the $CuSO_4$ concentration increases the bulk concentration of Cu^{2+} ions available in the electrolyte, thereby enhancing the transport of electroactive species to the cathode surface. According to electrochemical mass-transfer theory, the limiting current density is proportional to the bulk ion concentration, as expressed by

$$i_l = \frac{nFDC_b}{\delta}$$

where n is the number of electrons transferred, F is Faraday's constant, D is the diffusion coefficient, Cb is the bulk Cu^{2+} concentration, and δ is the diffusion-layer thickness [28]. Consequently, increasing the Cu^{2+} concentration increases the maximum rate at which copper ions can be supplied to the cathode. Under identical plating conditions, this generally promotes greater copper deposition during the fixed plating period, resulting in a thicker coating. Similar observations have been reported by Ye et al. [29], who found that increasing the metal-ion concentration in copper electrolytes enhanced the deposition rate and improved the morphology of the deposited coating. Likewise, Iksanudin

et al. [30] reported that electrolyte concentration significantly influences both copper coating thickness and corrosion characteristics of electroplated steel substrates.

The slight reduction in coating thickness observed at 0.55 N does not follow the overall increasing trend. However, the deviation is relatively small and, considering that each condition was measured only once without experimental replication, it is more likely to reflect normal experimental variability than a genuine physicochemical phenomenon. Potential sources of variation include minor differences in specimen positioning, local current distribution, surface preparation, and measurement uncertainty. Therefore, this isolated data point should be interpreted cautiously until confirmed by replicate experiments and statistical analysis. Overall, the results demonstrate that increasing the $CuSO_4$ concentration from 0.40 to 0.60 N generally increases the thickness of the copper coating deposited on the Fe substrate. This behaviour is consistent with electrochemical deposition theory, in which a higher Cu^{2+} concentration increases the availability of depositing ions at the cathode and consequently enhances the overall deposition rate under otherwise identical operating conditions.

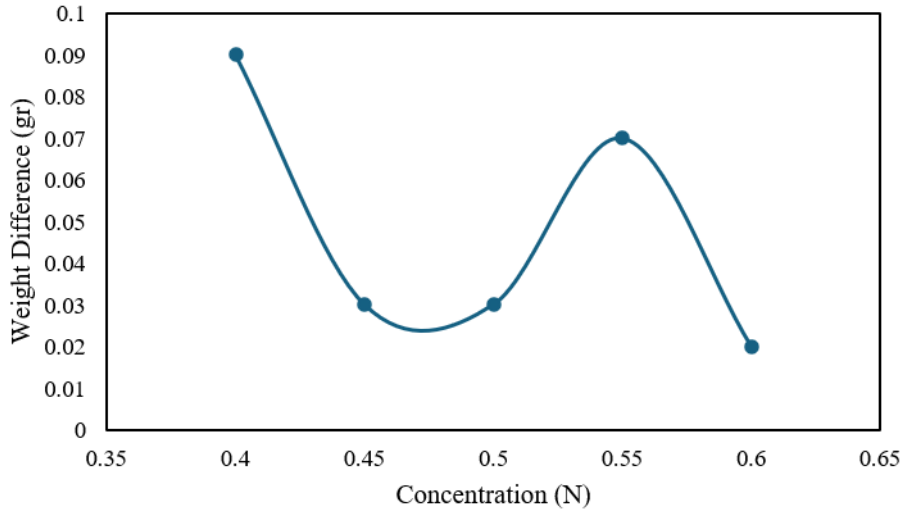

Figure 7. Effect of $CuSO_4$ Concentration on the Weight Gain of Fe Specimens after Electroplating

As shown in Figure 7, the weight gain of the Fe specimens after copper electroplating in $CuSO_4$ electrolytes with concentrations ranging from 0.40 to 0.60 N for 5 min varied between 0.02 and 0.09 g. The weight gain, calculated as the difference between the final and initial specimen masses, represents the mass of copper deposited on the substrate. The deposited copper exhibited a non-monotonic relationship with electrolyte concentration. The highest weight gain was observed at 0.40 N (0.09 g), followed by a decrease to 0.03 g at 0.45–0.50 N, a secondary increase to 0.07 g at 0.55 N, and a further decline to the minimum value of 0.02 g at 0.60 N. These findings indicate that increasing the $CuSO_4$ concentration did not proportionally increase the amount of copper deposited under the investigated experimental conditions.

The amount of deposited copper is governed not only by the total electrical charge supplied but also by the cathodic current efficiency, which determines the fraction of electrons utilized for Cu^{2+} reduction rather than competing side reactions, such as hydrogen evolution. Current efficiency is strongly influenced by the availability of Cu^{2+} ions at the cathode surface because the diffusion-limited current density increases with electrolyte concentration. However, when the applied current density approaches or exceeds the limiting current density, mass transport limitations become significant, promoting hydrogen evolution and reducing the efficiency of copper deposition. Under these conditions, the deposited layer may develop porous or dendritic morphologies with poor adhesion, resulting in partial detachment and consequently a lower measured weight gain[29]. Furthermore, the characteristics of electrodeposits are governed by the combined effects of deposition efficiency, deposit microstructure, and electrochemical operating conditions rather than electrolyte concentration alone, making non-linear deposition behaviour commonly observed in

electroplating systems[31]. Although electrolyte concentration generally enhances copper deposition and coating thickness on ferrous substrates [30], the irregular trend observed in this study suggests that additional factors, including local current distribution, bath composition, temperature, pH, and specimen-to-specimen variability, also influenced the deposition process. Because each electrolyte concentration was evaluated using only a single specimen without experimental replication or statistical analysis, the observed fluctuations should be interpreted with caution and cannot be regarded as definitive concentration-dependent trends. Future studies should incorporate replicate experiments, statistical evaluation, measurements of cathodic current efficiency, and microstructural characterization of the deposited coatings to distinguish intrinsic concentration effects from experimental variability.

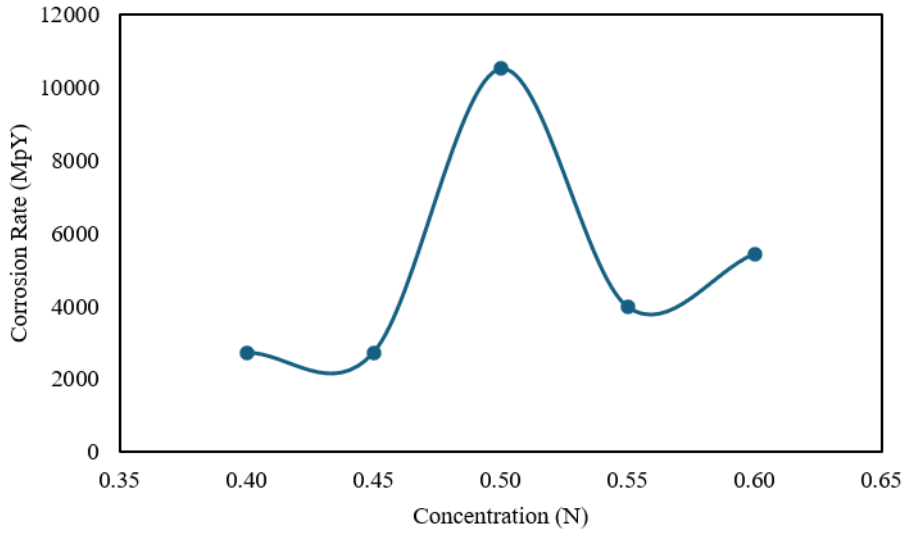

Figure 8. Correlation Between Concentration and Cu Corrosion Rate

Based on Figure 8. shows the relationship between concentration and corrosion rate of Cu metal. The graph shows the corrosion rate of Cu metal that has been dipped in $CuSO_4$ solution with a concentration of 0.4 N; 0.45 N; 0.5 N; 0.55 N; 0.6 N for 10 minutes respectively is 2720.551474 mpy; 2716.707077 mpy; 10519.82487 mpy; 3983.127848 mpy; and 5433.414154 mpy. Figure 3.3 shows a fluctuating graph. This is not in accordance with the literature, which states that increasing the concentration of the electrolyte solution has an impact on increasing the corrosion rate of the metal[32]. Oxidation-reduction processes have a strong relationship with corrosion, namely in the damage or degradation of metals because of redox reactions between metals and various substances in their environment. This reaction produces unwanted compounds[33]. Corrosion mechanisms in an electrochemical context involve anodic reactions. The anodic reaction, which is oxidation, can be identified through an increase in valence or the formation of electrons as products. In addition, the corrosion process also involves a cathodic reaction, which can be recognized through a decrease in valence value or the use of electrons generated from the anodic reaction[34].

A decrease in the corrosion rate of Cu metal can also be caused by factors such as cathodic protection, addition of corrosion inhibitors, modification of metal surface properties, or changes in corrosive environmental conditions[35]. The oxidation reaction takes place at the anode occurs in copper, were copper releases electrons. Meanwhile, a reduction reaction occurs at the cathode, which is the coated metal, where positive copper ions from the electrolyte solution accept electrons and precipitate as a copper layer on the coated metal. Through this process, there is a transfer of positive copper ions through the electrolyte solution to the cathode, where they accept electrons and undergo reduction to form a copper layer. Copper exhibits highly efficient thermal and electrical conductivity and has good corrosion resistance. In a balanced electroplating situation, the electrolyte concentration is fixed, while the anode is reduced over time. This leads to the deposition of metal coating the cathode, which is the object of work.

3.3. Effect of Surfactant Addition on Fe Electroplating with Cu

Table 5. Dimensions of Fe and Cu Metals Before and After Electroplating

Metals	Before				After			
	Long (cm)	Width (cm)	Height (cm)	Weight (gr)	Long (cm)	Width (cm)	Height (cm)	Weight (gr)
Fe	3.8	1.9	0.06	2.97	4	1.9	0.085	4.309
	3.9	2	0.06	3	4	2	0.085	4.35
	4	2.1	0.066	3.05	3.95	1.9	0.085	4.339
	4	2	0.065	2.89	3.95	1.9	0.085	4.369
	4	2	0.065	3.05	3.9	1.9	0.085	4.33
Cu	4	1.9	0.075	4.329	4	1.9	0.095	2.949
	3.9	1.9	0.079	4.35	4	2	0.095	2.99
	4	1.9	0.077	4.3695	4	2.05	0.09	3.03
	4	1.9	0.077	4.389	4	1.9	0.089	2.87
	3.9	1.9	0.078	4.39	4	2.1	0.091	3.049

Figure 9. Metal Condition after Electroplating

Table 6. Corrosion Rate Calculation Results of Cu Metal

Metal	Δ Weight (mg)	Density (g/cm^3)	A (in^2)	T (hours)	MpY	Concentration (N)	Surfactant (gr)
1	20.5		2.34422		6254.174		0.6
2	10		2.52774		2829.32		0.9
3	20	8.96	2.72881	0.166667	5241.696	0.5	1.2
4	19		2.6009		5224.497		1.5
5	1		2.6009		274.9735		1.8

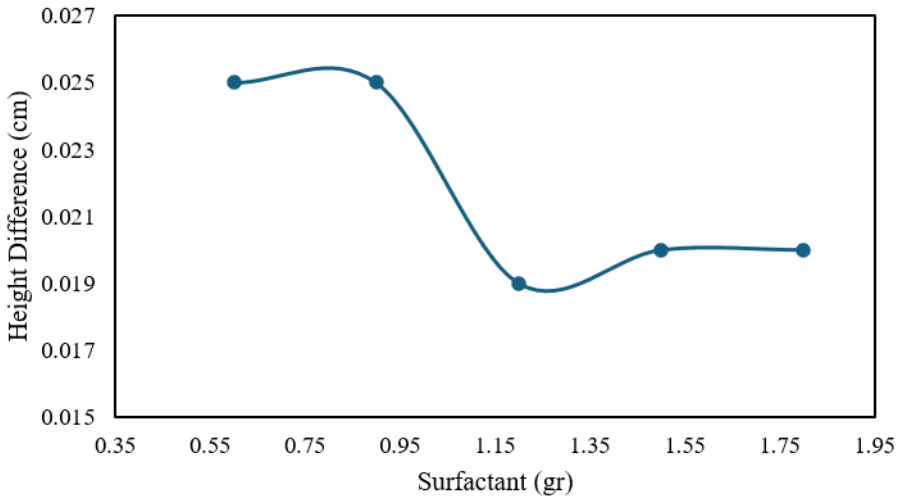

Figure 10. Effect of Surfactant on Fe Metal Thickness Variation

Figure 10 illustrates the relationship between the amount of boric acid added to the electrolyte and the difference in Fe metal thickness before and after the electroplating process. The results indicate that the thickness difference fluctuated with increasing boric acid addition at 0.6, 0.9, 1.2, 1.5, and 1.8 g, rather than exhibiting a continuous increasing trend. The highest thickness difference was observed at 0.6–0.9 g of boric acid, followed by a decrease at 1.2 g and a slight increase at 1.5–1.8 g. These results suggest that, under the present experimental conditions, increasing the amount of boric acid did not produce a proportional increase in coating thickness. According to the literature[36], boric acid primarily functions as a buffering agent in electroplating baths by stabilizing the electrolyte pH and suppressing hydrogen evolution on the cathode surface, thereby improving coating quality and deposition efficiency. However, excessive boric acid addition is generally avoided because of environmental and health concerns associated with its disposal and long-term exposure. The fluctuations observed in this study may also be influenced by other process parameters, including electrolyte temperature, pH, current density, electrode spacing, and local ion transport, all of which can affect the activation energy and deposition kinetics during electroplating. Furthermore, current density plays an important role in determining the deposition rate and coating quality, as higher current densities generally increase metal deposition, although excessively high values may also promote defects and non-uniform coatings. Since each experimental condition was evaluated only once, the observed variations should be regarded as comparative observations rather than definitive trends. Therefore, additional replicate experiments are recommended to verify the influence of boric acid concentration on coating thickness and to improve the statistical reliability of the results.

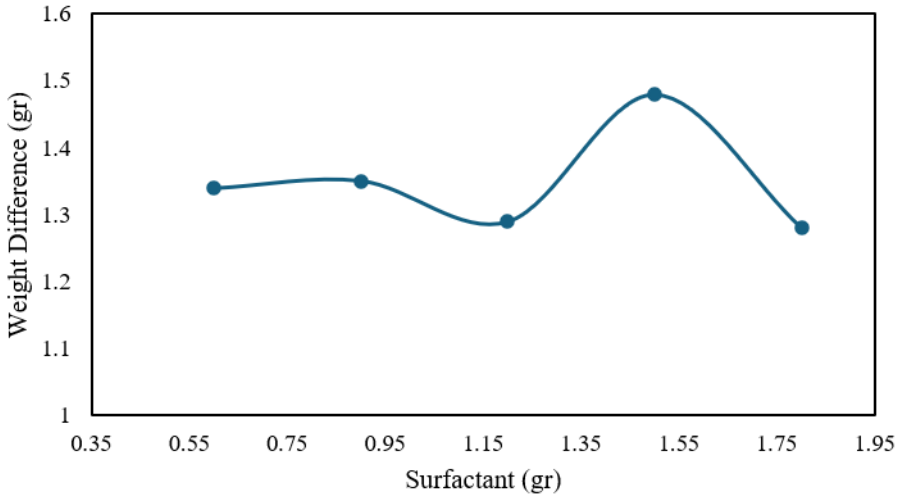

Figure 11. Effect of Surfactant on Fe Metal Weight Variation

Based on Figure 11, the addition of boric acid (surfactant) influenced the weight difference of the Fe coating, although the relationship was not linear. The weight difference fluctuated with increasing boric acid concentration, indicating that the amount of boric acid affects the electrodeposition process through changes in the electrochemical conditions of the electrolyte rather than by simply increasing the deposition rate. The highest weight difference was observed at a boric acid mass of 1.5 g, suggesting that this concentration provided the most favorable conditions for Fe deposition. At lower boric acid concentrations (0.6–1.2 g), the weight difference remained relatively stable. This indicates that the amount of boric acid present was sufficient to improve the plating environment but not enough to significantly alter the nucleation and growth mechanism of the deposited Fe layer. Boric acid has long been recognized as an important additive in electroplating baths because it helps stabilize the electrochemical environment near the cathode, suppresses excessive hydrogen evolution, and improves the morphology of the deposited metal layer. These effects contribute to a more uniform and compact metal coating with better current efficiency [37].

The maximum weight difference obtained at 1.5 g indicates the existence of an optimum boric acid concentration. At this concentration, boric acid likely promotes more efficient Fe deposition by minimizing localized pH fluctuations at the cathode surface and reducing defects caused by hydrogen gas evolution. Consequently, a greater amount of Fe ions can be reduced and deposited onto the substrate, resulting in a higher coating mass. Previous studies have also reported that boric acid improves deposit quality by influencing surface reactions, polarization behavior, and

hydrogen evolution during the electrodeposition of iron-group metals[38]. However, when the boric acid concentration was further increased to 1.8 g, the weight difference decreased. This reduction may be attributed to excessive adsorption of boric acid species on the cathode surface, which can partially block active deposition sites and hinder the transport of Fe^{2+} ions toward the electrode. As a result, the deposition efficiency decreases despite the higher boric acid concentration. Similar observations have been reported in electrodeposition studies, where excessive boric acid altered the polarization behavior and reduced the metal deposition rate because of competitive surface adsorption phenomena[39].

Overall, these results demonstrate that boric acid concentration is a critical parameter in the Fe electrodeposition process. Rather than exhibiting a direct proportional relationship, boric acid provides an optimum concentration that maximizes coating deposition. Below this optimum concentration, its beneficial effects on electrolyte stability and coating quality are limited, whereas concentrations above the optimum may reduce deposition efficiency due to excessive surface adsorption and mass transfer limitations. Therefore, under the operating conditions of this study, a boric acid mass of 1.5 g produced the highest Fe weight difference and is considered the optimum condition for electrodeposition.

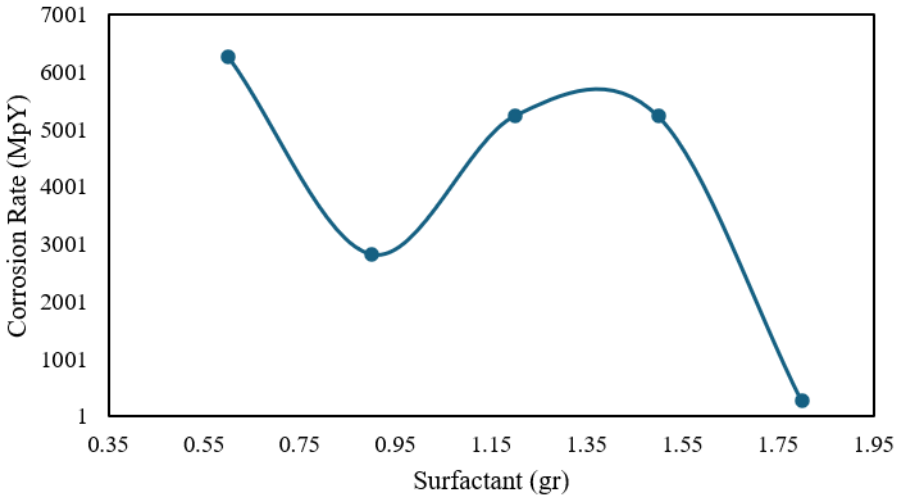

Figure 12 Correlation Between Surfactant and Cu Corrosion Rate

Figure 12. shows the effect of surfactant addition on the corrosion rate of copper metal. Based on the graph, it is known that the effect of the addition of surfactant with copper metal corrosion rate is fluctuating. This can be influenced by several factors, namely the presence of impurities in the metal layer and changes in solution temperature during electroplating, so that this is in accordance with the literature where, the addition of boric acid to the electroplating bath can reduce the corrosion rate if the electrolyte solution is at a stable temperature, where if the temperature rises followed by an increase in boric acid concentration, the reaction rate may increase. However, other literature sources explain that the addition of boric acid concentration in high temperature water, namely 573 K, can reduce the rate of metal corrosion.

4. Conclusions

This study investigated the effects of current density, boric acid addition, and $CuSO_4$ concentration on the electrodeposition of copper onto iron substrates. The results demonstrated that current density significantly influenced the amount of copper deposited and the calculated anodic corrosion-rate index. However, the relationships between current density and coating thickness, weight gain, and corrosion rate were non-monotonic, indicating that an optimum current density should be selected rather than simply applying the highest current density. The addition of boric acid, which functions primarily as a buffering agent in the electrolyte, contributed to improved deposition conditions and was associated with a substantial reduction in the calculated corrosion-rate index of the copper anode as the boric acid content increased from 0.6 to 1.8 g. Nevertheless, excessive boric acid concentrations should be avoided because of

their potential adverse effects on coating adhesion as well as environmental and health considerations. Among the $CuSO_4$ concentrations investigated, an intermediate concentration of 0.50 N produced the most favourable overall deposition performance, whereas both lower and higher concentrations resulted in comparatively less favourable outcomes. Within the experimental conditions evaluated, the combination of an intermediate current density, 0.50 N $CuSO_4$, and 1.8 g boric acid produced the most favourable overall performance. However, this conclusion should be regarded as preliminary and requires confirmation through replicated experiments.

Several limitations of the present study should also be acknowledged. The calculated corrosion-rate values were extrapolated from relatively short electroplating durations (5 min) and represent the dissolution behaviour of the copper anode rather than the corrosion resistance of the iron substrate. Consequently, these values should be interpreted only as a relative index for comparison among the investigated experimental conditions rather than as absolute measures of corrosion performance. Furthermore, important process variables, including electrolyte temperature, pH, and ambient humidity, were not monitored throughout the experiments. In addition, no control specimens or replicate measurements were included, and the electroplating duration varied among the experimental series, thereby limiting the statistical reliability and comparability of the results. Future studies should employ standardised electroplating durations, incorporate appropriate control samples and replicate measurements with statistical analysis (mean ± standard deviation), continuously monitor electrolyte temperature and pH, and evaluate the corrosion resistance of the coated iron substrate using standardised corrosion-testing methods, such as long-term immersion testing, potentiodynamic polarisation, or electrochemical impedance spectroscopy (EIS). These improvements would enable a more reliable assessment of coating performance and provide corrosion-rate values that more accurately reflect the behaviour of the coated iron substrate under service conditions.

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