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Temperature and Time Effects on Copper Electroplating Performance on Cu-Zn Alloys: Thickness, Conductivity and Corrosion Analysis

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ABSTRACT

In this work, the effects of bath temperature and plating duration on copper (Cu) electrodeposition onto brass (Cu-Zn) substrates from an acidic copper sulfate electrolyte were studied systematically in terms of buildup thickness as well as the electrical conductivity and corrosion resistance by means of depth profiling to identify quantitative processing-property relationships for optimization purposes in industrial settings. Copper electroplating at three temperature levels (25°C, 35°C, 45°C) and three plating times (2, 4, 6 minutes) was conducted using constant electrolyte composition (160 g/L $CuSO.5H_2O_4$, 70 g/L H_2SO_4) and applied current (1.5 A), allowing for systematic separation of temperature and time effects. Validation tests showed temperature greater than approximately 35°C were also associated with slightly higher susceptibility to corrosion, as indicated by an increase in the rate of corrosion penetration from salt spray exposure test (ASTM B117) after 72-hour period at temperatures between 25-35°C (4.157 mm/yr), versus 45°C (5.820 mm/yr). In addition, the longer 6-minute plating time led to excellent electrical conductivity with a resistivity of 4.082 mΩ/cm, indicating excellent electronic transport properties for electrical applications, while deposition efficiency decreased with extended plating times due to the onset of mass transport limitations in static bath conditions. The intermediate temperature of 35°C was identified as the optimal operating point, exhibiting suitable performance across various properties, obtaining considerable thickness while maintaining excellent corrosion resistance and conductivity at moderate energy consumption. The comprehensive dataset offers definitive process optimization recommendations, such as maximum productivity at 45°C, ideal corrosion resistance at 25–35°C, a 6-minute duration for optimal conductivity, and a combination of 35°C for 4 minutes for maximum versatility and general-purpose applications that provide balanced overall performance.

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1. Introduction

Copper electroplating on brass (Cu-Zn alloy) substrates is an extensively used technique in a variety of industries to create decorative hardware, connectors, and corrosion-resistant elements [1]. Despite its widespread popularity, systematic research continues to concentrate on the optimization of critical deposition parameters, such as bath temperature and deposition duration, for copper electroplating on brass substrates [1,2]. In numerous instances, the operators' insufficient control over the kinetics of these processes is a result of a lack of knowledge or information regarding the effective parameters that result in optimal coating quality and performance in relation to the operational cost [3]. Consequently, there is a necessity to gain a more comprehensive understanding of these processes.

Having a copper-to-zinc ratio of 55-95% makes brass alloys particularly challenging to electroplate [4]. According to Mohanty *et al*., [5], the electrochemical activity of zinc (E^o = -0.76 V) and copper (E^o = +0.34 V) can lead to the preferential dissolution of zinc in acidic electrolytes. This approach differs from the strategy for incorporating corrosion protection into coatings but may compromise adhesive interfacial bonding strength. Additionally, the exposure to the atmosphere results in the formation of a surface layer of zinc oxide that must be sufficiently removed to guarantee proper metallurgical bonding [6]. In addition, the crystallographic orientation and morphology of the electroplated layer will be affected by substrate composition as well as plating parameters like temperature and current density [7].

Temperature influences electrodeposition in multiple ways. This is facilitated on account of the Stokes-Einstein equation, whereby activation overpotentials and mass transport rates are accelerated [8]. Higher temperatures produce an increased Arrhenius-type behavior and exchange current density that dominates activation overpotential [9]. Previous study show that this lowering of current efficiencies could help to enable hydrogen evolution under extreme conditions. Su *et al*., [10] revealed that copper electroplating temperatures varies based on the substrate material, usually ranged from 20 to 60°C. Similarly, the deposition time is a critical factor in determining the final coating thicknesses and morphologies. Longer deposition periods result in thicker deposits, which may not enhance desirable characteristics, such as optimal grain structures or minimal internal tension [10].

As a result of the kinetic mechanisms that govern temporal dimensions, such as the diffusion layer formation, nucleation kinetics, and surface morphology evolution, the coating properties are affected by the time of plating in an analogous way [11]. The surface chemistry of zinc may complicate the initial deposition on brass substrates, which are generally limited by nucleation [12]. As the Nernst diffusion layer gets thicker during prolonged plating, the deposition rate will drop according to Fick's laws of diffusion [12,13]. This is because to problems with mass transport, like concentration polarization. Additionally, prolonged plating durations can lead to the development of dendrites or coarser deposits, especially at elevated current densities when growth is limited by charge transfer kinetics and diffusion [13].

Even though there is a lot of information on copper electroplating in the literature, researchers have not done any systematic research to look at how temperature and time interact with brass [14]. Moreover, to ascertain optimal processing intervals, it is essential to concurrently assess the cumulative effects of temperature and time on deposition efficiency and adhesion quality, even though most studies focus on pure copper or stainless-steel substrates [14].

This study investigates the copper electrodeposition from an acidic sulfate electrolyte (160 g/L $CuSO_4$, 70 g/L H_2SO_4) onto brass at three distinct temperatures (25°C, 35°C, and 45°C) and three plating durations (2, 4, and 6 minutes). This study seeks to elucidate the intricate interplay of the

physicochemical characteristics of copper coatings applied to brass, temperature, and plating duration. This research will be pivotal in the designing of ideal electroplating processing lines for industrial applications. This systematic approach provides empirical data as well as mechanistic insights into the optimal processing conditions for applications in industry, filling a gap in our current knowledge.

2. Materials and Methods

2.1 Substrate Preparation and Pre-Cleaning Process

The substrates were trimmed to 9.0 cm x 3.5 cm x 0.1 cm (height x width x thickness). Before the plating process began, the whole substrate went through pre-cleaning process to get rid of the oxide and make the copper alloy surface ready to be plated. This approach involves immersing the parts in de-oiling solution with 25 g/L each of NC-2cleaner (I) and NC-2cleaner (II), and the parts were subsequently rinsed with distilled water. The parts are then immersed in an activator solution consisting of 15 ± 5% H_2SO_4 and 160 ± 50 g/L Methanesulfonic Acid (MSA) and then again rinsed with distilled water to ensure the removal of residual chemicals prior to further processing.

2.2 Bath Composition

Electroplating of copper was performed on brass (Cu-Zn alloy) substrates in acidic sulfate electrolyte (160 g/L $CuSO_4 \cdot 5H_2O$, 70 g/L H_2SO_4). Brass substrates were standardized in terms of surface preparation prior to plating, which included alkaline degreasing (60-70°C, 5-10 minutes), water rinsing, and acidic pickling (10% H_2SO_4, 30 to 60 s), followed by a final deionized water rinse and immediate transfer into the plating bath.

2.3 Electroplating Procedure

Electroplating was performed using DC current in controlled-temperature bath (0.0015-0.0021 A/cm²). During plating (2, 4 or 6 minutes), the bath temperature was maintained at target values 35°C while during varies plating temperature (25°C, 35°C or 45°C) time was constant at 2 minutes with maintain the composition of sulfate solution 160 g/L $CuSO_4 \cdot 70$ g/L H_2SO_4. The setup comprised pre-treated brass cathodes (sample) and pure copper anodes deposited at a fixed distance from each other as shown in Figure 1. After drying, the samples were immediately rinsed with deionized water and air-dried.

2.4 Characterization Methods

The coating thickness was measured using cross-sectional imaging with an optical microscope equipped with image analysis software. EDS spectroscopy was used to validate the elemental composition and to confirm the copper was pure and find any other elements that were deposited at the same time. Electrical conductivity measurements for both copper coatings were recorded using a digital multimeter (Fluke) to measure the voltage and current supplied.

2.5 Corrosion Resistance Evaluation through Salt Spray Testing

The corrosion resistance of the electrodeposited copper coatings was assessed in accordance with ASTM B117, wherein samples were subjected to a 5% sodium chloride fog at a temperature of 35°C [15]. A 72-hour salt spray exposure test, which is the standard length of exposure time just enough for corrosion mechanisms to initiate and evolve but still practical for routine quality control

or process optimization, was performed on samples. This fast access test emulates severe marine or industrial environments [16]. Weight loss measurement, calculation of corrosive penetration rate, and change of coating thickness are three methods for determining corrosion.

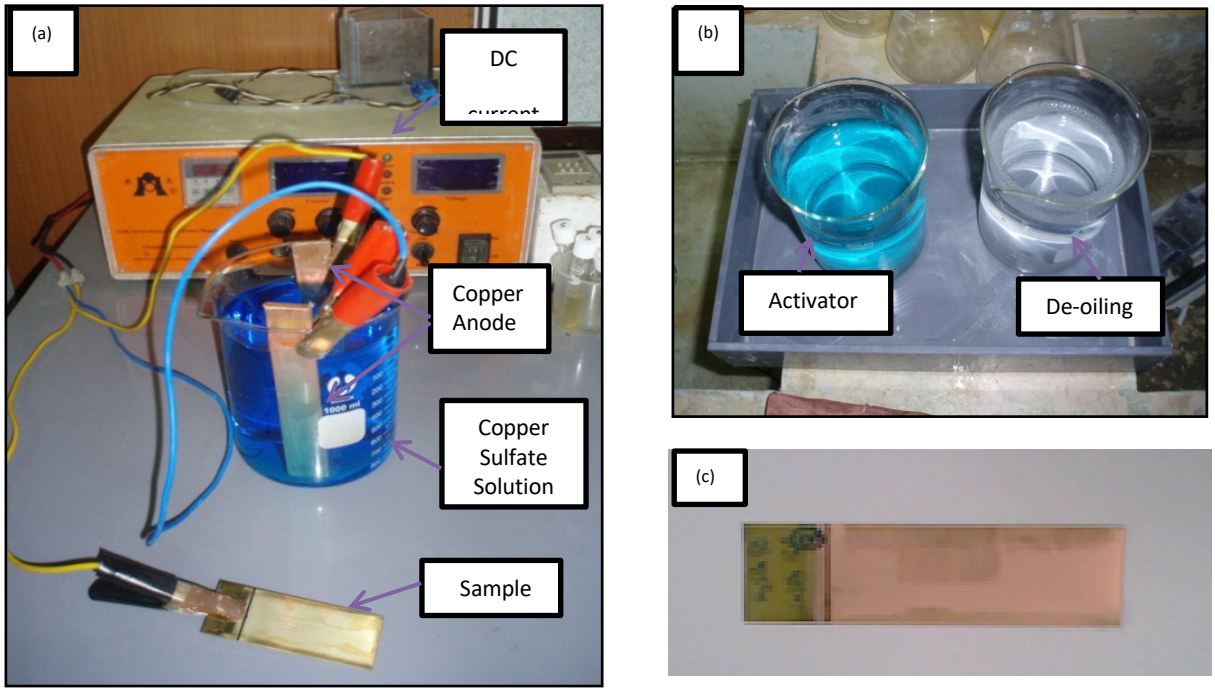

Fig. 1. (a) Setup equipment for copper electroplating (b) Pre-treatment composition (c) Sample after electroplating process

2.5.1 Weight loss measurement

The weight loss method quantifies material degradation by measuring mass before and after exposure to evaluate corrosion resistance through saline spray testing [17].

$$\Delta\text{Weight Loss} = W_{before} - W_{after} \quad (1)$$

where:

- W_{before}= Initial weight before salt spray exposure
- W_{after}= Final weight after exposure and corrosion product removal

2.5.2 Corrosion penetration rate

The corrosion penetration rate was determined using the following standardized equation [14]:

$$CPR = (K \times W) / (\rho \times A \times t) \quad (2)$$

where:

- CPR = corrosion penetration rate (mm/yr)
- K = constant for unit conversion (87.6 when using SI units to obtain CPR in mm/yr)
- W = weight loss after exposure time (grams)
- ρ = density of copper (8.96 g/cm³)
- A = exposed sample surface area (cm²)
- t = exposure time (72 hours)

This formula converts the measured weight loss into an equivalent depth of uniform corrosion (mm/yr), accounting for material density, sample geometry, and exposure duration.

3. Results and Discussion

3.1 Effect of Temperature on Coating Thickness

Figure 2 displays quantitative thickness measurements and cross-sectional microscopy of copper electroplated Cu-Zn alloys at varying temperatures (25, 35, and 45 °C). The immersion solution needs to have a current of 1.5 A, a plating period of 2 minutes, H_2SO_4 concentration of 70 g/L, and $CuSO_4$ concentration of 160 g/L. There are two separate parts that show the results. The top row includes optical microscopy images and EDS elemental analysis charts, while the bottom row displays bar charts that illustrate the measured values for each copper layer thickness across specimens, which were sampled at three marker locations from the top to the bottom. The EDS spot analysis data confirm elemental profiles for both coating and substrate regions, with abundant copper in the deposit and heightened levels of zinc are found to be localized within the Cu-Zn substrate area, as would be expected from a copper plating brass alloy system.

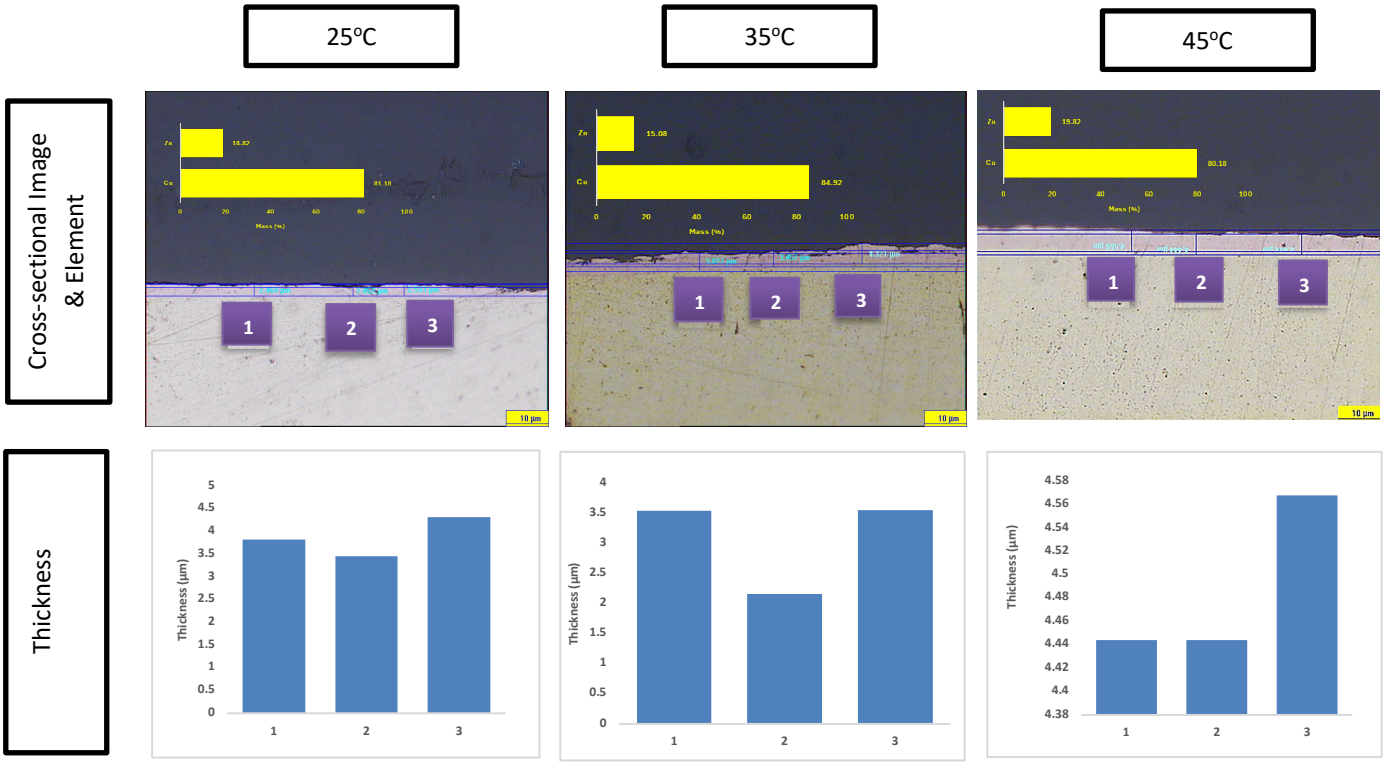

Fig. 2. Cross sectional with element and thickness for temperature varies

The uniformity of the deposition process is compromised as the bath temperature increases. At 25°C, the thickness values of the specimens varied from approximately 3.6 to 4.5 µm, suggesting a moderate degree of spatial uniformity across all observed surface areas. The thickness varies the most at 35 °C, where there is a transition from 2.3 µm (point 2) to 3.5 µm (1st and 3rd point). This variation indicates non-uniform deposition, suggesting the influence of ion transport properties specific to this intermediate temperature region and localized changes in current density distribution. On the other hand, higher average thickness values were displayed by sample prepared at 45°C, on account of a small variety of less than 4.44 µm - 4.57 µm. This indicates better homogenous deposition of copper over the surface of specimen with higher immersion temperatures.

The elemental composition analysis reveals distinct variations in copper and zinc distribution across the three temperature conditions studied. At 25°C, the coating exhibits a copper content of 81.18% with corresponding zinc at 18.82%, indicating substantial zinc incorporation from the brass substrate or electrolyte during the lower-temperature deposition process. Increasing the bath temperature to 35°C produces the highest copper purity at 84.92% and lowest zinc content of 15.08%, suggesting optimal conditions for selective copper deposition with minimal substrate dissolution or zinc co-deposition. At the maximum temperature of 45°C, copper content decreases slightly to 80.18% with correspondingly higher zinc levels, potentially reflecting enhanced thermal activation that promotes minor dezincification of the brass substrate or increased zinc ion mobility in the electrolyte. These compositional variations, while relatively modest across the temperature range studied, indicate that the intermediate temperature of 35°C provides the purest copper deposits with maximum selectivity, which correlates with superior electrical conductivity and optimal electrochemical efficiency observed at this condition.

Bath temperature, a very vital factor affecting the ability of copper electrodes to stick onto substrate Cu-Zn alloy. Figure 2 demonstrates this by displaying how the thickness varies with temperature. This intermediate temperature is transitional; at 35°C, the deposited copper exhibits non-uniformity as performance tends to be interrupted by competing electrochemical processes that prevent uniform nucleation and growth of the metal. And, because copper ions can move about more easily at elevated temperatures, deposition at 45°C was even more uniform than previously. This alleviates certain concentration polarization conditions on the electrode surface and accelerates electrocrystallization, resulting in a more homogeneous deposition [10].

3.2 Effect of Plating Time on Coating Thickness

As demonstrated in Figure 3, copper electrodeposition is also effective when deposited on a Cu–Zn alloy substrate over plating times of 2, 4 and 6 minutes at I = 1.5 A, T = 35 °C, H_2SO_4 =70 g/L and $CuSO_4$=160 g/L despite gradual expansion of the copper coating with increasing deposition time as seen from the cross-section micrographs. A thin and relatively uniform Cu liner is observed at 2 minutes. The coating is substantially thicker and more compact at 4 minutes, and the maximum thickness of the layer can be observed with complete surface coverage of the substrate at 6 minutes. This observation suggests that the kinetics of electrochemical deposition are consistent with the fact that coating accumulation is directly regulated by deposition time at a constant current density[18].

This time-dependent evolution of the coating is also corroborated by elemental analysis (EDS). At 2 minutes, the coating contains approximately 82 wt% Cu and 18 wt% Zn, indicating that a portion of the established Cu–Zn substrate is involved. At 4 minutes, the copper content rises to 91 wt% Cu, with a reduced contribution from Zn (9 wt%), indicating that the coating's purity and surface coverage have been improved. Nevertheless, the copper content decreases slightly to 85 wt%, while the zinc content rises to 15 wt% after 6 minutes. This variation may be the consequence of diffusion effects, localized microstructural heterogeneity, or measurement interaction with the substrate [5].

Three distinct locations illustrate a marked increase in coating thickness with time. The thickness for the 2-minute sample varies from range of 2.2 to 3.5 µm, at the 4-minute mark, it increases significantly to a range of 6.7 to 7.8 µm and continues with maximum coating thickness (8.2–8.5 µm) reached at the end of electrolysis. The linear correlation between time and thickness comes in accordance with Faraday's law as this relationship depicts deposition mass (or thickness) versus current flow during electrolysis. The key factor in this relationship is the constant current supply period for electrolysis [19].

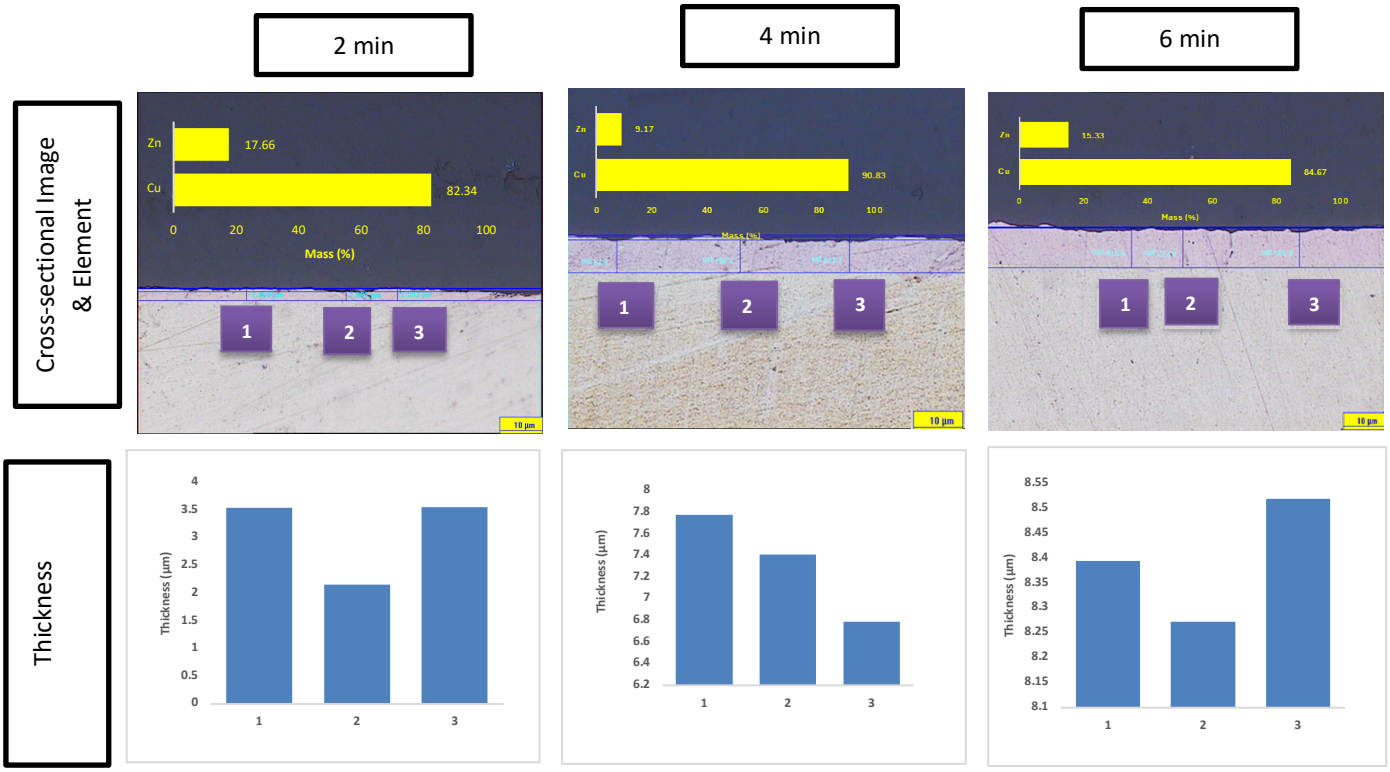

Fig. 3. Cross sectional with element and thickness for time varies

Therefore, the results suggest that the plating duration is a critical parameter that affects the compositional purity, coating thickness, and application performance. The 4-minute deposition produces the highest purity of copper and the most uniform thickness distribution, while the 6-minute deposition produces the densest copper layer. As a result, the 4-minute deposition appears to offer a more balanced electroplating condition in terms of coating integrity, conductivity potential, and thickness than other conditions.

3.3 Electrical Conductivity of Copper Coatings

Table 1 shows the results of the conductivity test for the copper electroplated Cu-Zn alloy sample in two different sets of experimental settings.The buffer temperatures (25°C, 35°C, and 45°C) and the plating periods (2, 4, and 6 minutes) are some of these circumstances. To get a full picture of how well the electroplated specimens worked electrically, we measured voltage (V), current (I), resistance (Ω), and resistivity (mΩ/cm). The current used in the tests stayed at 0.022 A the whole time. So, any changes in voltage, resistance, or resistivity that happened are to blame for the quality and properties of the copper layer that was deposited, not changes in the applied current.

The optimum resistivity of sample was observed as 4.082 mΩ/cm with a resistance of 0.1 Ω and maximum voltage value of 2.2 mV at 25 °C which is acceptable for all studied temperatures. The data shows a clear increase in electrical conductivity as the immersion temperature increases from 25 °C to 35 °C and from 35°C to 45°C, with resistance and voltage decreasing when the temperature of water is increased further to 35 °C and then up to second stage (up to 45 °C), for which it was drop down at the values of resistance (0.095Ω)and voltage Vector (2.1 mV). It also resulted in a decrease of the resistivity by 3.878 mΩ/cm. The thickness and morphology results correlate well with the improved electrical performance, since a more uniform and dense copper deposits itself at higher

temperatures. This reduces the overall resistance of the deposited layer in that it decreases the length each electron has to travel [20].

Table 1
Conductivity test result for temperature and time varies

Condition	Temperature Varies			Time Varies		
	25 °C	35 °C	45 °C	2 min	4 min	6 min
V(mV)	2.2	2.1	2.1	2.1	2.1	2.3
I (Amp)	0.022	0.022	0.022	0.022	0.022	0.022
Ω (ohm)	0.1	0.095	0.095	0.095	0.095	0.1
Resistivity (mΩ/cm)	4.082	3.878	3.878	3.878	3.878	4.082

The length of time the copper-plated specimens are coated also affects their electrical characteristics, which shows an interesting trend. The specimens that were plated for 2 minutes and 4 minutes had the same electrical properties such as a resistivity of 3.878 mΩ/cm, a resistance of 0.095 Ω, and a voltage of 2.1 mV. This means that the deposition of conductive copper was strong within two minutes of plating each unit with metal. Still, a resistivity of 4.082 mΩ/cm and a small voltage rise to 2.3 mV were reached within 6 minutes of plating, and the resistance rose to 0.1 Ω. The higher resistivity seen over longer plating times may be due to thicker deposits building up, which are linked to non-ideal microstructures or flaws, like grain development and internal tensions. These flaws can make conductance higher and make it harder for electrons to move through plated layers [21]. These findings indicate that there is an optimal time to plate. The electrical characteristics of the copper deposit are not improved by subsequent deposition, and they may even be marginally degraded.

3.4 Weight Loss Analysis

The weight loss of the copper electroplated Cu-Zn alloy specimens was measured to determine their corrosion behavior, as illustrated in Figure 4. Using weight loss data is a good way to figure out how resistant something is to corrosion [22]. This is because lower values mean that an electroplated layer is better at protecting against corrosive attacks from H_2SO_4 and $CuSO_4$ electrolyte solutions.

Each specimen weighed approximately 0.0015 g, and the weight loss values of the plated specimens were very similar at 25°C and 35°C. This implies that the copper deposits are formed at these two temperatures exhibit comparable corrosion resistance properties (Figure 4a). At 45 °C, there was a weight loss of only ~0.0021 g, which is a huge discrepancy between the weight losses. In other words, although at this temperature the homogeneity and thickness improved during sintering, the corrosion resistance decreased. This bizarre statistic is likely due to the residual stress inside or alteration in the microstructure of the copper deposit at its high temperature. This is responsible for local cracks or defects rapidly appearing, allowing corrosive media to penetrate the mounds and reach the underlying Cu-Zn substrate [23].

Figure 4(b) shows that there is a link between weight loss and plating time. This means that the corrosion weight loss is slowly going up and matches a longer deposition time. At the 2-minute post-plating timepoint, this was approximately 0.00155 g. At 4 minutes, there were moderate gains, which increased to 0.00163 g. At 6 minutes, the trajectory remained consistent, ultimately reaching approximately 0.00168 g. The consistent increase in the values of the three-time conditions, despite the minor variations, indicates that extended plating periods may not always improve corrosion protection; rather, they may cause a subtle deterioration in the barrier property of copper. This effect

is also corroborated by the conductivity results, as the 6-minute sample exhibited a lower conductivity than its antecedents. This means that copper-electroplated Cu-Zn alloy parts would have a balanced resistance to corrosion and electrical response within 2 to 4 minutes after plating.

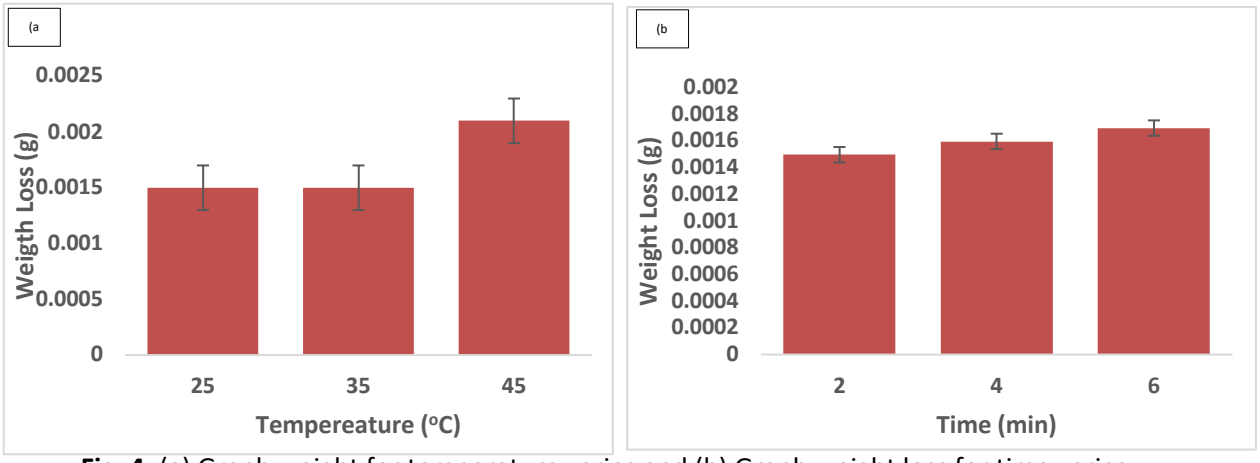

Fig. 4. (a) Graph weight for temperature varies and (b) Graph weight loss for time varies

3.5 Corrosion Penetration Rate Analysis

The Corrosion Penetration Rate (CPR) of copper electroplated Cu-Zn alloy specimens is depicted in Figure 5 in response to two experimental variables: buffer temperature (25°C, 35°C, and 45°C) and plating time (e.g., 2 minutes, 4 minutes, and 6 minutes). The Corrosion Penetration Rate (CPR) is a unit of 10^{-6} that makes it possible to estimate the speed at which corrosive attacks go through materials. Higher values are directly linked to a drop in the protective performance of electroplated layers and more aggressive penetration. The combination of CPR and weight loss could give us a better and more quantitative understanding of how electroplated samples corrode under different processing conditions. This would show that they are a better way to make stable structures than copper plating on the Cu-Zn component.

The weight loss results presented in Figure 4 are in excellent accord with these results, which exhibit very similar trends, as illustrated in Figure 5(a). In particular, the CPR decreases as the electroplating immersion temperatures rise. The correlation coefficients (R^2) at both 25°C and 35°C show that copper deposits developed throughout the range are similarly resistant to corrosive penetration. The results stay rather steady around 4.2×10^{-6} mm/yr. At 45°C, the CPR goes up by 38%, to about 5.8×10^{-6} mm/yr. This is way too much compared to the lower temperature conditions. Thus, the increase of penetration rate at 45°C suggests that a higher bath temperature can aid in thicker and more homogeneously copper deposits, but at the same time it can bring microstructural modifications to the deposit such as larger grains or pores and residual stress that could negatively affect the quality of metallic protective layer. Such rapid corrosive penetration of the underlying Cu–Zn alloy from heating [24].

The graph in Figure 5(b) supports the conclusions drawn from the weight loss study by showing a clear, steady rise in CPR as the plating time goes up. CPR was detected at an approximate value of 4.15×10^{-6} mm/yr after 2 minutes of plating. This value steadily increases to approximately 4.42×10^{-6} mm/yr and reaches a value of approximately 4.70×10^{-6} mm/yr after the plating duration is extended to 6 minutes.

In contrast to temperature, where the impact was significantly more rapid and was clearly observed at 45°C, the time-dependent progression of increased CPR is linear. This further implies that the cathodic barrier properties of the copper layer degrade gradually as the plating duration

increases, as evidenced by this study. This may also be attributed to the accumulation of internal stresses and the development of a columnar or coarsened structure in thicker deposits, which generates preferential pathways for corrosive species to permeate the layer [25]. The CPR data collectively demonstrates that the corrosion barrier performance of Cu-Zn alloys is inferior when plated at high temperatures or for an extended period. Conversely, the protective functionality is enhanced when the plating is conducted at moderate temperatures and for a lesser duration.

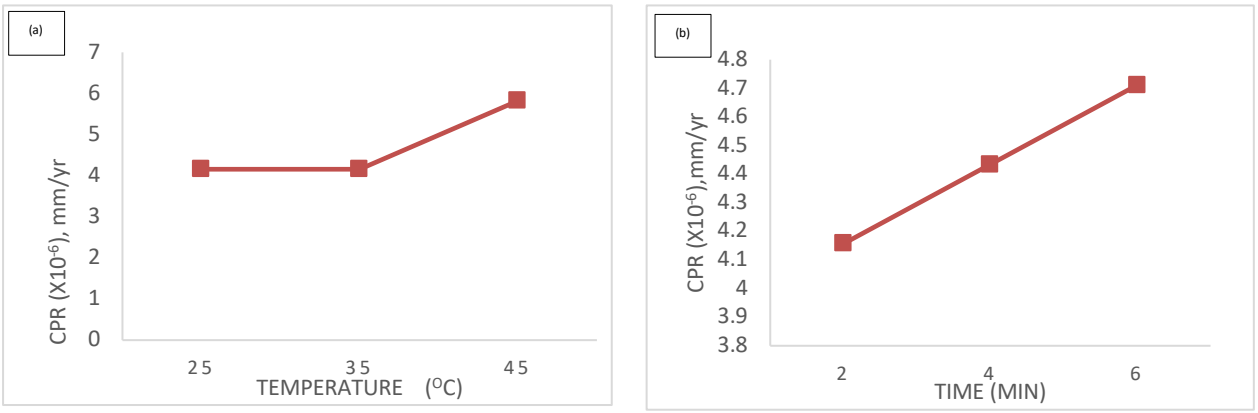

Fig. 5. (a) Corrosion Penetration Rate (CPR) for temperature varies (b) Corrosion Penetration Rate (CPR) for time varies

3.6 Coating Thickness Reduction After Corrosion

When the copper electroplated Cu-Zn alloy is exposed to accelerated corrosive conditions, the primary goal of Figure 6 is to demonstrate the degree of degradation that it undergoes. To accomplish this, cross-sectional microscopy images are presented from specimens that were subjected to varying conditions, while maintaining constant I = 1.5 A, T = 35 °C, H_2SO_4 = 70 g/L, and $CuSO_4$ = 160 g/L. The corresponding thickness measurements are obtained after the salt spray corrosion test. The plating time of the specimens was 4 minutes. The accelerated corrosion evaluation method known as the salt spray test is widely accepted [26]. Specimens are placed in a saline environment that is very corrosive and is controlled by temperature and humidity [16,26]. This test replicates a long-term corrosive attack to see how well the electroplated layer protects a wide range of materials.

Figure 3 shows that the average value before the salt spray test is about 7.3 µm. The cross-sectional microscopy and the bar chart photos show that the copper coating become a lot thinner after the salt spray test. After the test, the thickness values at points 1, 2, and 3 were 4.1 µm, 3.6 µm, and 3.0 µm, respectively. This means that the bad conditions that were seen throughout operation caused the original coating thickness to drop to an average of about 3.24 µm. The cross-sectional examination demonstrates that the coating interface was less distinct and more irregular compared to the pretest, suggesting that localized corrosive attack and simultaneous dissolution of copper transpired during saline spray exposure. Surface degradation was evident in these observations in Figure 6. The results thus indicate that the copper electroplated coating can indeed offer a significant degree of corrosion protection to a Cu-Zn substrate. Long-term exposure to very salty settings can cause a lot of material loss [27]. To get the best density, homogeneity, and thickness, the electroplating parameters must be tuned. This will make the product last longer [10,28].

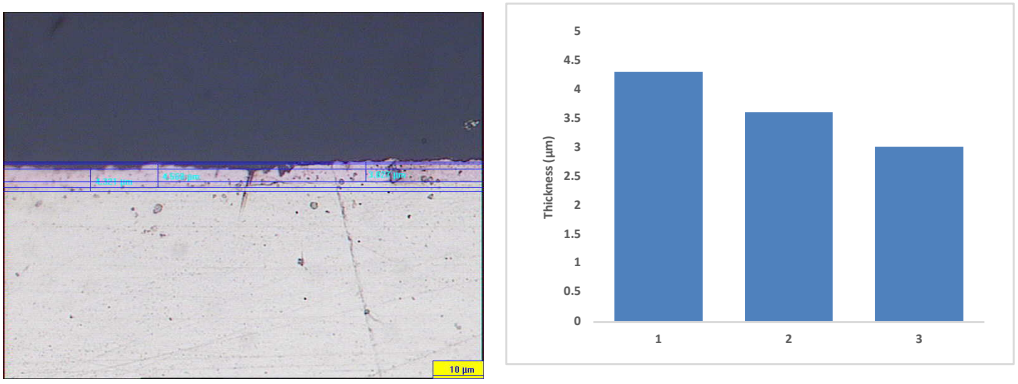

Fig. 6. Thickness after salt Spray Test for 4 minutes time varies with I = 1.5 A, T = 35 °C, H_2SO_4 = 70 g/L, and $CuSO_4$ =160 g/L

4. Conclusions

This study employed an acidic copper sulfate electrolyte to conduct a systematic investigation of copper electroplating on brass substrates over a range of temperatures (25–45°C) and plating durations (2–6 minutes). The results indicated that 45°C was the most effective temperature for maximizing coating thickness and productivity, while 35°C achieved an optimal balance of thickness, conductivity, and corrosion resistance. Superior electrical conductivity of 4.082 mΩ·cm was attained through extended plating for 6 minutes; however, the returns were diminishing as a result of mass transport constraints. Across all conditions, salt spray testing confirmed satisfactory corrosion resistance, with a CPR of 4.157–5.820 mm/yr. The results indicate that 35°C with a 4-minute plating time is the most suitable general-purpose condition. However, the parameters can be modified to accommodate application-specific priorities, such as productivity, conductivity, or corrosion protection.

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