

Process Optimization of Electroless Copper Plating for Printed Circuit Boards

Xiaohui Song¹ *, Wanji Liu², Lei Wang², Benqin Jing¹

¹ Guilin University of Aerospace Technology, Guilin 541004, China;

² Guilin Shiyu Electronic Technology Co., Ltd. Guilin 546612, China.

232784151@qq.com

Abstract. Due to the non-uniform copper deposition, through-hole metallization failure, high product defect rate, and insufficient high-frequency and high-speed signal transmission performance, this paper optimized the electroless copper plating process, including: swelling, desmearing, pre-neutralization, neutralization, hole-conditioning and degreasing, micro-etching, pre-dipping, activation, acceleration. The results showed that PCBs achieved 100% continuous coverage of electroless and electrolytic copper layers on via walls, with backlight ratings reaching Grade 10. Interfaces were well-defined, copper cross-sections dense and uniform, and via-wall coatings smooth and continuous with excellent corner coverage. Copper thickness was stable with CV $\leq$ 26.1% and TP up to 96.00%.

Keywords: PCB; electroless copper plating; Opmization

1. Introduction

Although printed circuit boards (PCBs) cost only 5-10% of the total finished circuit board assemblies, their reliability is critical. Especial through-hole metallization is the core process for achieving interlayer interconnection in PCBs. Among these steps, the quality of electroless copper plating directly determines the success of through-hole metallization[1].

There are some issues during conventional electroless copper plating processes, such as incomplete contamination removal, insufficient rinsing after desmearing and neutralization, inadequate micro-etching, and uncontrolled activation parameters. These issues lead to defects including non-uniform copper deposition, hole wall separation, unstable backlight ratings, and short electroless copper bath life. In order to solve these issues, meaningful research has been carried out by scholars worldwide. Xu et al. [2] used orthogonal experiments to analyze the micro-etching parameters in the pretreatment stage of electroless copper plating, identifying sodium persulfate concentration, copper ion concentration in the etchant, temperature, sulfuric acid content, and etching time as the main factors affecting the micro-etching rate. Pan et al. [3] investigated the variations in palladium and copper contents in electroless copper deposits on copper-clad laminate substrates of two different resin systems treated with various desmearing processes. Yang [4] and Xiao et al. [7] separately analyzed the causes of backlight failure in electroless copper plating and proposed corresponding improvement measures. He et al. [5] determined that copper particles were primary constituent of copper sludge by using cross-section analysis. They optimized aeration piping for more even bubbling, added an auxiliary bath to lighten the production load, and used polyquaternary ammonium salts to stabilize the electroless copper bath. These changes reduced the copper sludge clogging defect rate from 3.2% down to 0.25%. You [6] proposed an optimization method for the electroless copper plating process. Ha et al. [7] presented a high-resolution direct writing technique via femtosecond laser multi-pulse-induced thermochemical deposition of copper from glyoxylate-copper complex inks modified with surfactants. This paper proposed an optimization route and procedure for the electroless copper plating process, and calculated the backlight rating, surface copper thickness, hole wall copper thickness, and throwing power to verify the quality of electroless copper plating.

2. Experimental and Testing Methods

Five double-sided copper-clad laminates with different holes diameter were adopted. All chemical reagents used were industrial-grade mass-produced products. Experiments were performed on an industrial vertical electroless copper plating line with thermostatically controlled baths.

Samples were embedded in epoxy resin, ground by using diamond abrasive disks, and polished to a mirror finish on the via cross-section to avoid chamfering, scratches, or eccentric deformation of the hole walls. A metallurgical microscope was adopted to explore hole-wall of samples at 100× magnification using transmitted light (bright field off). The light was compared with a standard backlight rating chart to determine the backlight grade (1-10 Grade). The minimum and average ratings of the tested vias were recorded.

Using a metallurgical microscope, copper thickness was measured at the upper opening, center, and lower opening of each via on both sides, with three repeated measurements at each position to obtain average values. Surface copper foil thickness was measured simultaneously. The average copper thickness, minimum copper thickness, throwing power (TP), and range coefficient (CV) were calculated using Equations (1)–(3):

$$\bar{T} = \frac{\sum_{i=1}^n T_i}{n} \quad (1)$$

where $\bar{T}$ is the average copper layer thickness, T_i is the measured copper thickness at a single point, and n is the total number of measurement points.

$$TP = \frac{T_{hole-min}}{T_{hole-avg}} \quad (2)$$

where TP is the throwing power (coating uniformity), $T_{hole-min}$ is the minimum hole wall copper thickness at the via center, and $T_{hole-avg}$ is the average copper thickness at the via openings.

$$CV = \frac{T_{max} - T_{min}}{\bar{T}} \quad (3)$$

where CV is the copper thickness range coefficient reflecting in-panel thickness uniformity, and T_{max} and T_{min} are the maximum and minimum copper thickness values measured on the test panel, respectively.

3. Optimization Scheme for Electroless Copper Plating Process

The electroless copper plating process consists of core steps including desmearing, degreasing, activation, and copper deposition, as shown in Figure 1. Key controlled parameters include desmearing level, copper content in the micro-etchant, palladium concentration in the activation solution, and composition of the electroless copper bath.

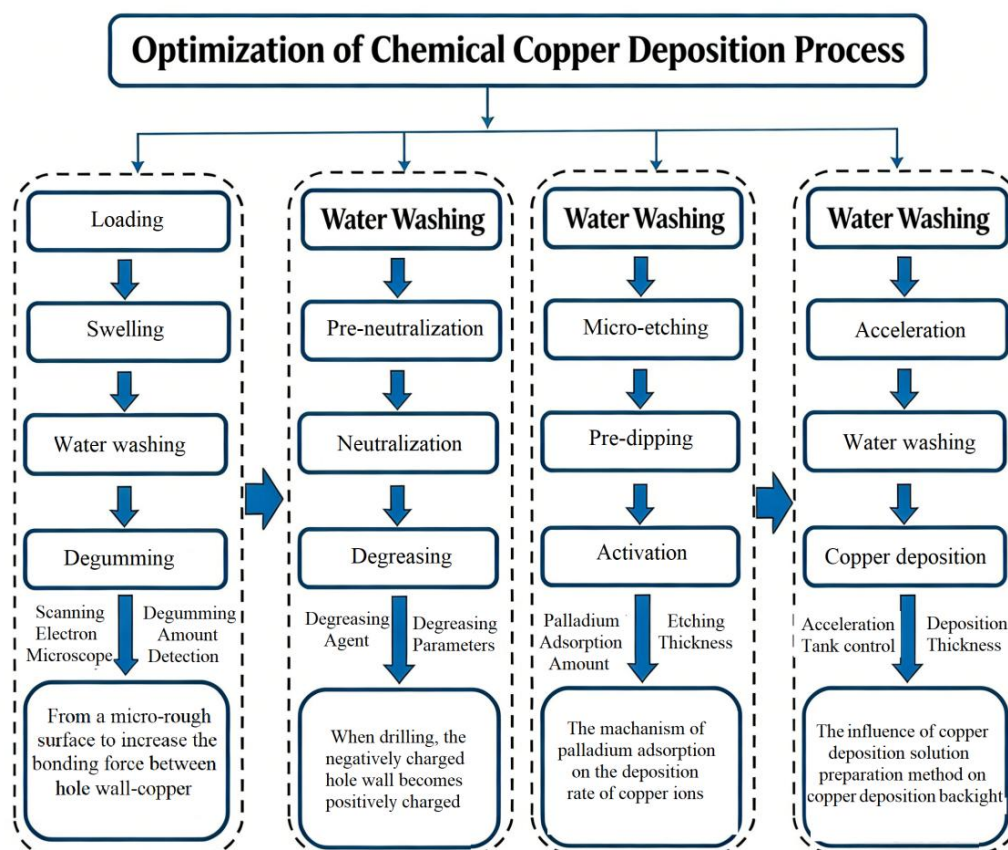


Figure 1 Optimization of Electroless Copper Plating Process

(1) Optimization of Swelling and Desmearing

The substrate was treated with a swelling agent with concentration of 32–38%, temperature of 70–80 °C, and treatment time of 5–7 min to ensure sufficient softening of epoxy resin and to avoid excessive substrate swelling. A potassium permanganate–sodium hydroxide system was used for desmearing (KMnO_4 concentration 50–60 g/L, NaOH concentration 38–43 g/L, temperature 70–85 °C, treatment time 15–20 min). The desmear weight was controlled at 0.1–0.5 mg/cm² to remove drill smear without excessive substrate etching.

(2) Optimization of Pre-neutralization and Neutralization

A sulfuric acid–hydrogen peroxide mixture was used for pre-neutralization: H_2SO_4 concentration 0.5–1.5%, H_2O_2 concentration 0.5–1.5%, temperature 20–32 °C, treatment time 0.5–1.2 min to preliminarily reduce residual oxidizing substances. A sulfuric acid–strong acidic reducing agent system was then applied: H_2SO_4 concentration 4–6%, reducing agent concentration 15–25%, temperature 35–45 °C, treatment time 4–6 min to completely remove residual MnO_2 , KMnO_4 , NaOH , and other contaminants.

(3) Optimization of Hole Conditioning, Degreasing and Micro-etching

An alkaline degreaser was used at 8–10% concentration, 55–65 °C, for 5–8 min to remove organic contaminants and adjust the hole wall surface charge. Hot water rinsing was applied afterward to enhance chemical residue removal. A sodium persulfate–sulfuric acid system was used for micro-etching: $\text{Na}_2\text{S}_2\text{O}_8$ concentration 60–83 g/L, H_2SO_4 concentration 2–5%, temperature 28–35 °C, treatment time 1–2 min. The copper ion content in the bath was below 30 g/L, and the micro-etching rate maintained at 1–2 μm (optimum 1.5 μm) to achieve uniform surface roughening.

(4) Optimization of Pre-dipping and Activation

A pre-dip salt–hydrochloric acid system was employed: pre-dip salt 180–220 g/L, HCl 2–5%, treatment time 2–5 min at room temperature. Direct transfer to activation without intermediate rinsing prevented contamination of the activation bath. The activation bath consisted of pre-dip salt, HCl , and colloidal palladium: pre-dip salt 180–220 g/L, HCl 3–5%, colloidal palladium 1.2–1.6%,

temperature 38-42 °C, treatment time 6-8 min. Acidity, specific gravity, and palladium concentration were regulated to ensure uniform and continuous adsorption of palladium nuclei on the hole walls.

(5) Optimization of Acceleration

A weakly alkaline accelerator with pH buffer was used to treat at 38-42 °C in 1.7-3.1 min. The accelerator concentration was 8-12% with pH 8.4-9.1. This process fully exposed palladium catalytic sites while preventing palladium particle detachment, ensuring uniform catalytic activity.

(6) Electroless Copper Plating

The electroless copper solution was a ternary system composed of copper complex concentrate, copper-formaldehyde concentrate, and NaOH concentrate. Key composition was: Cu^{2+} 1.2-1.6 g/L, HCHO 3-6 g/L, NaOH 7-11 g/L; copper complex concentrate 6-8%, copper-formaldehyde-NaOH concentrate 3-6%. Process parameters were set as: temperature 38-42°C, plating time 18-25 min, deposition rate 1-2 μm (optimum 1.25 μm). Optimization of the complexing system significantly improved bath stability, suppressed copper powder formation, and ensured uniform copper deposition on via walls.

4. Results and Discussion

Cross-sectional images of thin PCB samples after plating are shown in Figure 2. Among them, sample 2 and 5 are thin plate, others are thick plate. All five samples exhibited 100% continuous coverage of the electroless copper base layer and subsequent electrolytic copper layer on via walls. Transmitted-light backlight testing showed no light leakage, pinholes, voids, or exposed substrate; all samples achieved the maximum backlight rating of Grade 10.

This indicated complete copper crystallization without discontinuities, reliable adhesion between the coating and substrate, and elimination of critical defects such as poor backlight, voids, and local substrate exposure. Electrical reliability of through-hole metallization was fully guaranteed. All samples showed clear interfaces between substrate copper foil and plating, without delamination, blistering, or peeling.

The copper cross-sections were dense and uniform, with no pits, nodules, burrs, or other visible defects. The thickness on the top and bottom surfaces was nearly consistent, showing stable deposition performance. The coatings on the via walls were compact, smooth, and continuous, without protrusions, voids, or cracks. No chamfering, scratches, or deformation caused by sample preparation was observed.

Samples 1, 4, and 5 had the most even coating distribution, with almost no thickness gradient and no dog-bone effect (thicker at the openings, thinner in the middle). Samples 2 and 3 only showed slight thickness variations within the acceptable industrial range, and no obvious abnormal morphology was found. The coatings at the via corners transitioned smoothly without thinning, exposure, or cracking, proving good step coverage.

In terms of thickness uniformity, no obvious local thickness fluctuations appeared. The minimum and average copper thickness on the via walls were very close, and the coefficient of variation (CV) of all samples was controlled within 26.1%, which means the plating quality was stable at different positions and apertures.

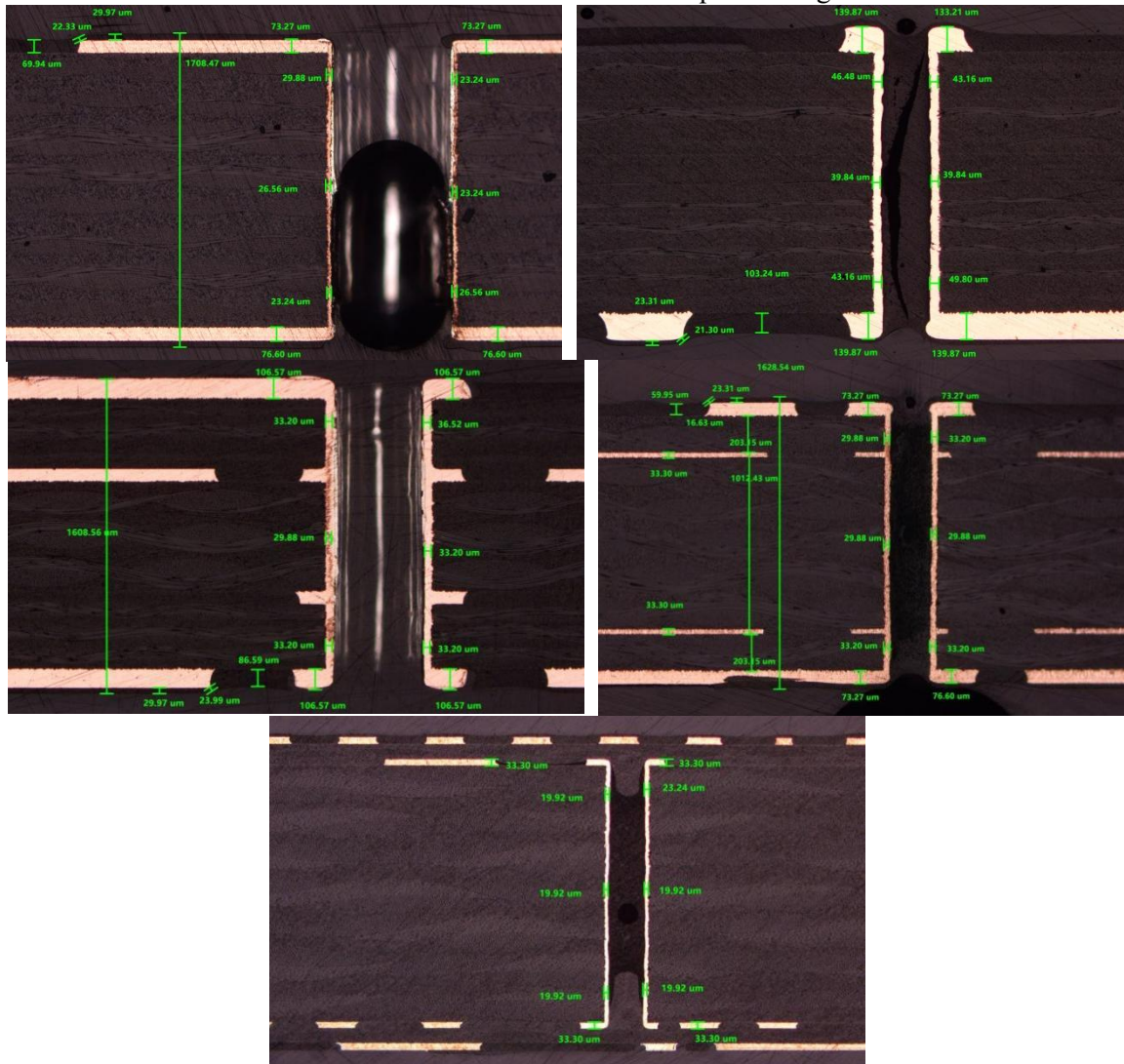


Figure 3 Test image of electroless copper plating sample

Table1 Quality of electroless copper plating samples

No.	Backlight Grade of Hole Wall	Average Surface Copper Thickness (μm)	Average Hole Wall Copper Thickness (μm)	Minimum Hole Wall Copper Thickness (μm)	Maximum Hole Wall Copper Thickness (μm)	Throwing Power TP (%)	Range Coefficient CV (%)
1	10	74.94	25.45	23.24	29.88	90.32	26.1
2	10	139.87	43.71	39.84	49.80	87.27	22.8
3	10	106.57	33.20	29.88	36.52	87.80	20.0
4	10	74.10	31.54	29.88	33.20	92.31	10.5
5	10	33.30	20.47	19.92	23.24	96.00	16.2

Throwing power (TP) values of all samples far exceeded the industrial qualification standard (TP $\geq 80\%$). Sample 5 reached 96.00%, and Sample 4 reached 92.31%. Sufficient deposition was maintained at via centers, avoiding the common problem of insufficient center coating in high-aspect-ratio holes.

5. Conclusions

This study optimized the electroless copper plating process for PCBs to address existing process deficiencies. Both thin PCBs and thick high-aspect-ratio PCBs achieved 100% continuous coverage of electroless and electrolytic copper layers on via walls, with backlight ratings reaching the optimal Grade 10. Interfaces were well-defined, copper cross-sections dense and uniform, and via-wall coatings smooth and continuous with excellent corner coverage. Copper thickness was stable with $CV \leq 26.1\%$ and TP up to 96.00%.

6. Acknowledgements

This work was supported by the Guangxi Science and Technology Program Project: Research on Optimization of Electroless Copper Plating Process for PCB with Uniform Copper Distribution (No. 2023AB01248).

7. References

- [1] Lin J D, Gong Y L. Advanced Modern Printed Circuit Technology [M]. Beijing: Chemical Industry Press, 2019.
- [2] Xu Y T, Zhang T Z. Application of orthogonal experiment in electroless copper micro-etching [J]. Printed Circuit Information, 2010(3): 19–21.
- [3] Pan W H, Wang X B. Effect of different desmearing processes on palladium and copper content in electroless copper deposits [C]//Proceedings of the 26th China CCL Technology Symposium, 2025.
- [4] Yang Y J. Analysis and improvement of backlight failure in electroless copper plating [J]. Printed Circuit Information, 2013(6): 12–15.
- [5] Xiao Y S, Luo X M, Deng T. Improvement of backlight defects in electroless copper plating [J]. Printed Circuit Information, 2012(11): 28–31.
- [6] He N, Lian C Y, Feng Z H, et al. Improvement of copper sludge in electroless copper plating [J]. Printed Circuit Information, 2024, 32(S2): 62–70.
- [7] You K. A desmearing method for circuit board electroless copper plating [P]. Jiangxi Province: Longnan Junya Electronic Technology Co., Ltd., 2023-07-18.