Simulation and Experimental Study on Metal Microstructure of Meniscus-Constrained Electrodeposition

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Meniscus-constrained electrodeposition (MCED), as one of the multifunctional additive manufacturing methods for microsensor manufacturing and flexible electrical interconnection, has great potential in future miniaturized communication devices. At present, however, the understanding of the multiphysical field processes involved in this method, such as electrodeposition, fluid dynamics, and mass and heat transfer, is limited, and the deposition forming process has not yet been well explained. Herein, the manufacturing process of metal microstructure used by MCED is studied, and the contour features of the microstructure are characterized. Simultaneously, based on the law of liquid phase mass transfer in microzone, the theoretical model of MCED process is established, the important role of Marangoni effect in evaporation process is revealed, and the effect of evaporation process on MCED is analyzed and discussed. Besides, the effect of evaporation process on the dynamic process of deposition is further proved by simulation analysis. The additive manufacturing equipment based on MCED is built to manufacture metal microstructure. Furthermore, the effects of evaporation on the morphology, roundness, vertical angle, and chemical composition of deposited metal microstructure are analyzed experimentally. These results provide a promising platform for the direct fabrication of nanocircuit interconnections, microsensors, and microantennas.

1. Introduction

With the wide application of micro–nano electronic devices in modern electrical field, great changes have taken place in the manufacturing methods of microcomponents. Microcutting has strong 3D machining ability and high process stability, but the cutting speed is low and the tool wear is serious. Besides, microelectrical discharge machining (micro-EDM) has no requirement for the strength and hardness of metal materials, and the macroscopic cutting force is small, but the wear and tear of microelectrode is inevitable and the clamping stability of microelectrode is low. In addition, although the tool cathode of microelectrochemical machining (micro-ECM) has no wear and thermal stress, the machining precision is not high, the design of the tool cathode is troublesome, and the cycle is long. In contrast, localized electrodeposition technology is a typical additive manufacturing technology in which metal microstructure is fabricated layer by layer in the form of atoms. It offers a number of advantages such as high precision, good surface quality, flexible implementation, and easy operation. Therefore, it may have more development advantages and applications in the metal microadditive manufacturing. Up to now, several electrodeposition techniques directly oriented to 3D metal microstructure manufacturing have been developed such as jet electrodeposition (Jet ECD), localized electrodeposition (LECĐ), electrochemical printing (EcP), and meniscus-constrained electrodeposition (MCED).

In 1956, Jet ECD was first proposed by Zimmerman. Jet ECD has dense deposition structure and fast deposition speed. However, it witnesses poor locality, the deposited metal grains are not stable, and has difficulty generating 3D metal microstructure with high aspect ratio. LECĐ, first proposed by Madden and Hunter in 1985, has great advantages in the manufacture of complex free bodies, and it is easy to control the microstructure and properties of the deposition structure. Despite its advantages, it also comes with a number of drawbacks, including low deposition rate, poor surface quality, low precision, and many pores. In addition, in 2003, EcP was first proposed by Whitaker. EcP has some advantages in the preparation of thin-layer micropatterns but there is no breakthrough in the formation of 3D complex structures.

In 2010, MCED was introduced by Jie Hu and Min-Feng Yu in an article published on Science. It relies on a glass micropipette with electrolyte. When the nozzle of the pipette is close to the substrate, a continuous and stable liquid meniscus can be formed between the end of the nozzle and the substrate. An electrochemical reaction occurs inside of the meniscus under the action of an external electric field to form a metal microstructure with 3D shape characteristics on the conductor substrate. Compared with other electrochemical 3D microdeposition techniques, MCED has the advantages of high forming precision and the ability to fabricate complex linear structures. Seung Kwon Seol et al. printed metallic microarchitectures with controlled internal structures and performed numerical simulation by employing a finite element method (FEM) to verify the...
dependence of the concentration distribution of the Cu ions. Seyedreza Morsali et al. used the multiphysical finite element simulation method to study the effects of nozzle velocity and nozzle diameter on MCED under the guidance of experimental data. In addition, a computational model including L-PED process was proposed to explain the current hypotheses in the literature on formation of nt-metals by stress relaxation during the OFF-time. Yuan-Liu Chen et al. carried out an experimental study on the online current monitoring of MCED metal microstructure, and through the calculation of the geometry of the meniscus, a simulation model was established and multiphysical simulations were carried out. Fuyue Zhang et al. analyzed the factors influencing the microscale MCED with COMSOL Multiphysics and found the appropriate range of variables used during the experiments.

Although MCED has been widely used to fabricate complex microstructures, this method involves multiphysical field processes such as electrodeposition, fluid dynamics, mass transfer, and heat transfer. The deposition process is complex, the law of influence has not been well revealed, and the theoretical research on the multiphysics model based on dynamic process is still rare. In this work, we study the process of MCED of metallic microstructure, and characterize the contour features of the microstructure. Based on the law of liquid phase mass transfer in microzone, the theoretical model of MCED process has been established, and the effect of evaporation process on MCED has been analyzed and discussed. The multiphysical field simulation of the whole MCED process has been carried out, and the influence of evaporation process on the deposition dynamic process has been further analyzed and discussed. Then, the MCED experimental system was set up and MCED of metallic microstructures by utilizing a prototype was performed. The morphology, contour, and composition of metal microstructure were observed.

2. Model Building

As shown in Figure 1, in the MCED process, the glass pipette filled with metal salt solution moved slowly toward the conductive substrate. When the distance between the glass pipette and the conductive substrate was small enough, the meniscus would form between them without direct contact, and hence the localized electrical deposition process could be controlled through the meniscus. Under the bias voltage between the wire (anode) and the conductive substrate (cathode) in the metal salt solution, the MCED occurred only in the meniscus region, and the pure metal was deposited on the conductive substrate. Under the condition of keeping the meniscus between the glass pipette nozzle and the conductive substrate, the metal microstructure with a certain height and diameter can be deposited by slowly leaving the glass pipette from the conductive substrate. The height and diameter of the metal microstructure depend on the order of magnitude of the glass pipette nozzle.

MCED has its own special features, as shown in Figure S1. Fabrication of metallic microstructures using this process is a complex multiphysics process in which electrodeposition, fluid dynamics, and mass and heat transfer physics are simultaneously involved. The main principles involved include the Marangoni effect, Nernst–Planck law, Nave–Stokes law, and Butler–Volmer.

The mass transfer process of MCED is realized by diffusion, electromigration, and convection of metal ions. Compared with the traditional electrodeposition technology, the mass transfer process of MCED is mainly affected by water evaporation on the surface of the meniscus. The temperature gradient will cause uneven relative humidity on the surface of the meniscus and water evaporation on the surface of the meniscus. The thin liquid film thickness and low heat transfer resistance of the extended meniscus formed near the solid–liquid–gas three-phase contact angle of the meniscus lead to a large heat transfer coefficient and more significant water evaporation.

The mass transfer process of MCED is shown in Figure 2. On the one hand, water evaporation takes water from the surface of the meniscus, and copper ions are detained, which directly affects the local concentration near the extended meniscus. On the other hand, water evaporation absorbs heat from the surface of the meniscus, which will cause obvious temperature changes.
and hence form a temperature gradient $\nabla T$, and finally produce the Marangoni effect near the meniscus, causing convective flow $u$ inside the meniscus from the inside to the outside. It aggravates the convective flux $ciu$ inside the meniscus, directs copper ions to the surface of the meniscus, and increases the local concentration near the extended meniscus. Because the diffusion, electromigration, and convection which are mainly involved in the mass transfer process are all related to the concentration, with the increase of the local concentration, the diffusion $D_i\nabla ci$, electromigration $ziu_ciF\varphi$, and convection $ciu$ will also increase accordingly. This behavior will eventually affect the whole mass transfer process and produce positive feedback to the local concentration near the meniscus, forming a dynamic cycle.

$$
\begin{align*}
    c_i &= \frac{m_i}{M_i(V - \Delta t(D_c\nabla c_i + M_c\nabla \nu))} \\
    -p + \mu(\nabla \vec{u} + (\nabla \vec{u})^T) - \frac{2}{3}\mu(\nabla \cdot \vec{u}) &= \gamma \nabla \cdot T \\
    J_i &= -D_i\nabla c_i - z_iu_ciF\varphi + c_i\vec{u} \\
    \frac{\partial c_i}{\partial t} + \nabla \cdot J_i &= 0
\end{align*}
$$

where $u$ is the fluid velocity; $p$ denotes the fluid pressure; $\mu$ is the dynamic viscosity of the fluid; $T$ is the temperature; $\gamma$ is the temperature derivative of surface tension; $c_i$ is the concentration of the ion $i$; $m_i$ is the mass of ion $i$; $M_i$ is the molar mass of ion $i$; $V$ is the volume of electrolyte solution; $A$ is the surface area of meniscus; $t$ is the time; $D_c$ is the diffusivity of water vapor in the air; $M_v$ is the molar mass of water vapor; $c_v$ is the water vapor concentration; $v$ is the velocity of water vapor; $J_i$ is the transfer flux of ion $i$; $D_i$ is the diffusivity of ion $i$; $z_i$ is the electronic charge of ion $i$; $u_i$ is the mobility of ion $i$; $F$ is the Faraday constant; and $\varphi_i$ is electric potential difference in the electrolyte.

3. Simulation Analysis

As there is relative motion between the glass pipette and the conductive substrate in the deposition process, and the deposition process is dynamic and changes with time, the multiphysical field finite element analysis software COMSOL Multiphysics was used to simulate the physical processes of electrodeposition, fluid dynamics, and mass and heat transfer in the MCED process to further explore the influence of water vapor evaporation on the dynamic process of MCED.

3.1. Geometry

In this study, the FE analysis was based on the experimental parameters. Among them, the meniscus shape of MCED geometric model is described by Equation (2).

$$
z(r) = -R \sin \alpha_0 \ln \frac{r + \sqrt{r^2 - R^2 \sin^2 \alpha_0}}{r_0 + \sqrt{r_0^2 - R^2 \sin^2 \alpha_0}}
$$

where $R$ is the radius of deposited metal microstructure; $r_0$ is the radius of glass pipette nozzle; $\alpha_0$ is the growth angle, that is, the angle between the tangent line of the meniscus and the upper surface of the deposited metal microstructure; $\alpha_0 = 90^\circ - \varphi_0$.

Because of the symmetry of the geometric model, a 2D axisymmetric FE simulation model was used in the simulation process (Figure 3a). The geometric model represents a glass pipette filled with metal salt solution and connected to the upper surface of the deposited metal microstructure through the metal salt solution meniscus. In this study, the metal salt solution used to deposit metal microstructure was a mixture containing 0.5 M CuSO4 solution, 51 mM H2SO4, and 0.48 mM HCl. The 2D axisymmetric cylindrical coordinate system and the Z axis were used in the vertical direction.

3.2. Boundary Condition

The electrolyte of the simulation model consists of H2SO4 and HCl mixed with CuSO4 solution, which was placed in a glass pipette in an air environment with controllable humidity. The boundary conditions are shown in Figure 3b. The ion transfer in the electrolyte region was controlled by the Nernst–Plank formula of the electrolyte.

$$
J_i = -D_i\nabla c_i - z_iu_ciF\varphi + c_i\vec{u}
$$

where $J_i$ is the transfer flux of ion $i$; $D_i$ is the diffusivity of ion $i$; $c_i$ is the concentration of the ion $i$; $z_i$ is the electronic charge of ion $i$; $u_i$ is the mobility of ion $i$; $F$ is the Faraday constant; and $\varphi_i$ is the electric potential difference in the electrolyte.

Fluid flow in meniscus is controlled by Navier–Stokes formula.
\[
\rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \nabla \cdot (\mu (\nabla u + (\nabla u)^T)) + F \tag{4}
\]

where \( \rho \) is the fluid density and \( F \) is the external force.

In order to make the simulation results as close to the actual situation as possible, the dynamic process of deposition was carefully observed. According to the experimental conditions, the diameter of the deposited metal microstructure was designed to be 70 \( \mu \)m, the diameter of the glass pipette nozzle was designed to be 100 \( \mu \)m, the electrolyte concentration was 0.5 m \( \text{CuSO}_4 \), 51 mM \( \text{H}_2\text{SO}_4 \), and 0.48 mM \( \text{HCl} \), the ambient temperature was 25 \( ^\circ \)C, the ambient relative humidity was 40%, and the deposition time was set to 600 s. In addition, in the humidity-controlled environment, there is no environmental change in the electrodeposition process, so the simulated evaporation process is regarded as a time-independent process.

3.3. Simulation Results

The multiphysical field simulation results are shown below. Figure 4 shows the variation of relative humidity near meniscus with time during MCED. Figure 5 indicates the variation of evaporation flux near meniscus with time during MCED. Figure 6 illustrates the variation of total flux in meniscus area with time during MCED. As can be seen from the relative humidity cloud map, relative humidity gradients were observed near the meniscus at an ambient humidity of 40%. Specifically, the relative humidity near the meniscus was higher, close to 100%. As a matter of fact, the electrodeposition process was in a humidity-controlled environment, the relative humidity did not change obviously with time. When the deposition time was 0 s, there was an evaporation flux near the meniscus due to the relative humidity gradients, which would cause convection on the meniscus surface. Among them, the evaporation flux near the

![Figure 3](image.png)

**Figure 3.** a) Schematic of the computational geometry. b) Boundary conditions in finite element model.

![Figure 4](image.png)

**Figure 4.** The variation of relative humidity near meniscus with time during MCED: a) 0 s, b) 180 s, and c) 600 s.

![Figure 5](image.png)

**Figure 5.** The variation of evaporation flux near meniscus with time during MCED: a) 0 s, b) 180 s, and c) 600 s.
solid–liquid–gas three-phase contact angle of the meniscus was more significant, with a peak value of 7.94 × 10⁻⁶ kg m⁻² s⁻¹. Thus, the total flux in the edge region was 19.12 × 10⁻³ mol m⁻² s⁻¹, slightly higher than that in the central region. Interestingly, as the deposition time was increased to 180 s, with the glass pipette moving up slowly, the evaporation flux increased to 9.01 × 10⁻⁸ kg m⁻² s⁻¹. Due to the short evaporation time, the total flux only fluctuated slightly, with a peak value of 19.65 × 10⁻⁴ mol m⁻² s⁻¹, and the distribution did not change obviously. Therefore, the deposited metal microstructure (red frame area) showed growth with a flat-top. By contrast, when the deposition time was 600 s, the evaporation flux increased significantly as high as 23.90 × 10⁻⁸ kg m⁻² s⁻¹, especially near the solid–liquid–gas contact angle of the meniscus. Thus, the total flux in the central region of the meniscus decreased, and the total flux in the edge region increased to 23.07 × 10⁻³ mol m⁻² s⁻¹. The deposited metal microstructure (red frame region) showed the trend of edge preferential growth. On the other hand, the results show that although evaporation takes away water from the surface of the meniscus over time, the dynamic deposition process does not change the shape of the liquid surface, and the overall deposition structure grows vertically.

4. Experimental Section

The schematic diagram of additive manufacturing equipment based on MCED is shown in Figure 7. The whole MCED system consisted of a coarse XYZ three-axis motion stage, a XY three-axis motion stage, a Z-axis nanomotion stage, a potentiostat module, and a glass pipette filled with metal salt solution (0.5 M CuSO₄; 51 mM H₂SO₄; 0.48 mM HCl). The coarse XYZ three-axis motion stage moved the glass pipette above the conductive substrate with a motion stroke of 500 mm and a positioning resolution of 10 μm per axis. The XYZ three-axis motion stage was used to make the conductive substrate close to the glass pipette with a motion stroke of 25 mm and a positioning resolution of each axis of 10 μm. The Z-axis nanomotion stage was used to control the Z-axis relative motion of the conductive substrate and the glass pipette during electrodeposition with a motion stroke of 12 mm and a positioning resolution of each axis of 0.1 nm. The potentiostat module connected the conductive substrate with the anode silver wire for generating current between the electrodes.

The parameters used in this experiment are shown in Table 1. In the experiment, a glass pipette with an aperture of 100 μm was used and filled with metal salt solution in which the anode silver wire was placed. A wafer with a thickness of 0.5 mm was selected as the conductive substrate and cut by a diamond cutter into a piece of 15 × 15 mm squares. One side was chosen to be plated with a titanium layer of 15 nm, followed by a copper layer of 100 nm. The prepared conductive substrate was placed into the acetone solution for ultrasonic cleaning for 60 s. The substrate was then rinsed with isopropyl alcohol (IPA) and deionized water to remove organic and inorganic impurities. The nitrogen stream was used to dry the rinsed matrix. The interelectrode current was set to −20 μA, the ambient temperature was room temperature (25 °C), and the ambient humidity was 40%.

In the course of the experiment, a stable meniscus has to be formed between the conductive substrate and the glass pipette nozzle. For this purpose, the glass pipette was first moved above the conductive substrate by the coarse XYZ three-axis motion stage, and the conductive substrate was slowly close to the glass pipette filled with metal salt solution through the XYZ three-axis motion stage under the visualization system. When the conductive substrate was in contact with the metal salt solution at the nozzle of the glass pipette, the XYZ three-axis motion stage was moved in the opposite direction in a way ensuring that a meniscus was formed between the conductive substrate and the glass pipette nozzle. The potentiostat module was used for electrodeposition, and the conductive substrate was kept away from the glass pipette at an appropriate speed to maintain a stable meniscus by the Z-axis nanomotion worktable, thus limiting the electrodeposition reaction to the meniscus area to prepare metal microstructure.

In addition, the contour of the microstructure was captured by laser confocal microscope (LSM), and the surface morphology was characterized by scanning electron microscope (SEM). The chemical composition of metal microstructure was measured by field emission electron probe microanalyzer (EDS).

5. Results and Discussion

First, the morphology of metal microstructure prepared by MCED method was observed. The 3D morphology and surface morphology of the microstructure were studied by LSM and SEM. Figure 8 shows LSM and SEM images of the metal microstructure at different times. Figure 8a–d shows the observation results with a deposition time of 180 s. It is found that the outer contour was rounder. Although the upper surface was smooth,
defects were detected. It may be explained that there are defects for the glass pipette nozzles used in electrodeposition, and the meniscus is not completely attached to the conductive substrate during the formation of the meniscus. Figure 8b,e shows the observation results with a deposition time of 300 s. It is observed that the outer contour and the upper surface did not change significantly, and no defect was found. Besides, the metal microstructure showed a trend that the growth rate at the edge of the upper surface was slightly higher than that at the center.

Figure 8c,f shows the observation results with a deposition time of 600 s. The outer contour exhibited poor roundness, and the edge of the upper surface was slightly higher than the central area, which is consistent with the simulation results. It is understood that evaporation causes convection flow on the surface of the meniscus, so that the total flux in the edge area of the meniscus is larger than that in the central region, resulting in a higher growth rate of the edge region of the meniscus than that in the central region. The phenomenon that the edge did not grow at a higher speed at the deposition time of 180 and 300 s can be explained by the fact that the evaporation time at the beginning of deposition is short, and the copper ion concentration is uniformly distributed on the conductive substrate. With the increase of time, the water near the meniscus gradually evaporates, which increases the copper ion concentration at the edge of the meniscus, resulting in a higher growth rate of the edge region than that in the central region. Additionally, a protruding structure was observed on the upper surface of the metal microstructure. The reason for this is that it grows faster than that of the glass pipette, during the growth process, and hence the gap between the poles becomes shorter and the current density increases, leading to uneven growth.

In order to further explore the influence of evaporation process on the actual external profile of metal microstructure, the roundness and vertical angle of the metal microstructure were measured. With the help of the MATLAB software, the roundness was measured by the least square method. The outer circle and the inner circle of the actual outline of the metal

| Parameter                  | Value                                                                 |
|----------------------------|----------------------------------------------------------------------|
| Copper ion solution        | CuSO₄ (0.5 M); H₂SO₄ (51 mM); HCl (0.48 mM)                          |
| Glass pipette aperture     | 100 μm                                                               |
| Interelectrode current     | −20 μA                                                              |
| Ambient temperature        | Room temperature (25 °C)                                             |
| Environment humidity       | 40%                                                                  |
microstructure were measured, and the difference between the radius of the inner and outer circle was taken as the roundness error. The detection target used in the measurement process was the LSM image of the metal microstructure. In the detection process, only the complete target circle was found by the given target size and target position, and the incomplete circle was removed to prevent the program from detecting the wrong target. The measurement result is shown in Figure 9. It can be seen from the figure that the metal microstructure had a good roundness, and the roundness ranged from 2.6 to 2.9 with an average of about 2.8. The results show that during the deposition process, the meniscus has a good roundness, and evaporation occurs uniformly at the edge of the whole meniscus, resulting in the uniform diffusion of copper ions to the edge of the meniscus. The reason for the small fluctuation of the roundness of the metal microstructure may be that there is a certain deviation in the circular section of the joint between the meniscus and the conductive substrate formed in the actual deposition process. Due to the different glass pipettes used in many experiments, there is a deviation in the roundness of each glass pipette nozzle, which changes the roundness of the meniscus, resulting in a small fluctuation in the roundness of the metal microstructure.

Figure 10 shows the measurement of vertical angle of the metal microstructure. In order to describe the vertical angle of a circle of the outer contour of the metal microstructure, the metal microstructure was divided into eight equal parts and four angles (8 points) were selected for measurement. Taking the center of the metal microstructure as the center and the horizontal line passing through the center as the reference, four angles were selected: horizontal line 0° position, vertical line 90° position, clockwise rotation 45° position, and 135° position. Figure 10a–d corresponds to the outline details of the metal microstructure marker position (red line) in the upper right corner, respectively. By using MATLAB software, the linear curve fitting was carried out for the data of the junction between the metal microstructure and the conductive substrate in the contour details, and the vertical angle of the metal microstructure was calculated by the slope $k$ of the fitting curve. The calculation formula is as follows

$$\alpha = \arctan k$$

(5)

As shown in the figure, it can be seen that the metal microstructure had a good vertical angle, ranging from 89.02° to 90.2° with an average of about 89.65°. This phenomenon demonstrates high consistency with the simulation results with the deposition time of 600 s where evaporation takes away water from the surface of the meniscus without changing the shape of the meniscus, and the microstructure of deposited metal grows vertically as a whole. Moreover, it is seen that the contour details of the four angular positions were higher at the edge than in the central region, which further verifies the simulation results that evaporation causes convection flow on the surface of the meniscus, resulting in a higher growth rate of the edge region of the meniscus than that of the central region.

Next, the chemical composition of the metal microstructure prepared by MCED was further studied. The chemical composition in the metal microstructure was measured by field emission electron probe microanalyzer. Figure 11 shows energy-dispersive
Figure 10. Measurement of vertical angle of metal microstructure. a–d) are the outline details of the marking position (red line) in the LSM image of the metal microstructure to be detected.

Figure 11. a) The EDS diagram obtained from the metal microstructure. b) The energy spectrum of the selected area (red circle) shows the deposition of pure copper without impurities.
X-ray spectroscopy (EDS) analysis. On the one hand, oxygen in the air will be dissolved in the electrolyte because MCED is carried out in an indoor environment. On the other hand, the deposited copper structure experiences rapid rate of oxidation in the indoor environment, forming copper oxide on the surface of the microstructure. The temperature, however, is reduced due to evaporation in the MCED process, so that the surface of the metal microstructure is not easy to oxidize. Figure 11a shows the EDS diagram of the selected area (red circle) of the detected metal microstructure. It is indicated that the microstructure contained only copper and oxygen. Among them, copper was more abundant and distributed more densely while oxygen was rare and more dispersed with a granular oxygen concentrated spots. This is because the surface of the metal microstructure is not completely flat, there are very fine steps, and the edge of the step is easily oxidized, so that more oxygen is concentrated near the step, forming a granular oxygen concentrated spots. Figure 11b shows that the copper content in the selected area was as high as 99.0 wt%, confirming that the metal microstructure is of high purity copper structure and that there is no obvious oxygen (oxygen content <1.0 wt%).

6. Conclusions

In summary, the process of MCED of metallic microstructure is simulated and experimentally studied in this article. 1) First, the theoretical model of MCED is established, and the evaporation process affecting MCED is analyzed and discussed. The multi-physical processes of electrodeposition, fluid dynamics, and mass and heat transfer in MCED process are analyzed, the important role of Marangoni effect in evaporation process is revealed, and the theoretical model of water evaporation on MCED mass transfer process is proposed in an innovative way. 2) Second, combined with the theoretical model, the multi-physical field simulation of MCED is carried out, and the dynamic process of electrodeposition affected by evaporation is further discussed. Under the humidity-controlled environment, the relative humidity near the meniscus does not change with time, and the evaporation flux and the total flux at the edge of the meniscus increase gradually with time. When the deposition time is 180 s, due to the short evaporation time, there is only a small difference in the total flux between the edge region and the central region of the meniscus, and the deposited metal microstructure shows growth with a flat-top. When the deposition time is 600 s, the total flux in the edge region of the meniscus is obviously higher than that in the central region. The deposited metal microstructure shows the trend of edge preferential growth. 3) Finally, an additive manufacturing equipment based on MCED has been built and the effect of evaporation on metal microstructure was studied by MCED method. Through the analysis of LSM images and SEM images, it can be seen that with the change of time, the convective flow caused by evaporation makes the edge of the metal microstructure gradually higher than the central area. By measuring the outer outline of the metal microstructure, the average roundness is about 2.8 and the average verticality is about 89.65°. It shows that evaporation occurs uniformly on the surface of the meniscus and does not change the shape of the meniscus. In addition, the field emission electron probe spectrometer was used to test the chemical composition of the metal microstructure. The experimental result reveals that the copper content exceeded 99.5%, proving that the deposited structure is an almost pure metal printing.

Although the MCED method can be used to fabricate the microstructure of high purity copper with good roundness and verticality, the bulge structure will appear on the upper surface with the increase of deposition height, which will affect the deposition quality. To improve the surface quality of the electrodeposition, the next step of the study is to further optimize the theoretical model of MCED, and explore the mechanism of the effect of current density on the upper surface of the microstructure by establishing the relationship between the current density and the surface quality of the microstructure.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (grant no. U19A20103); Applied basic Research Project of key R&D Program of Changchun Science and Technology Bureau (grant no. 21ZY37); The Fund for the Central Government Guides Local Science and Technology Development Funds to the special basic research of Jilin Province (grant no. 202002039J).  

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

contour features, dynamic process, evaporation, Marangoni effect, meniscus-confined electrodeposition

Received: May 4, 2022
Revised: August 7, 2022
Published online: September 14, 2022

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Adv. Eng. Mater. 2022, 24, 2200654
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