## **Electroforming Process to Additively Manufactured Microscale Structures**

Krish Patel, Amelia McNamee, Bishal Silwal

Department of Mechanical Engineering, Georgia Southern University, Statesboro, GA 30458

## Abstract

Electroforming is a metal forming process that forms parts through electrodeposition. The overall study and production of the copper mandrel were conducted by examining the growth and depth of the depositions at macroscopic levels. The study of the plating constant for a copper plate in copper sulfate was performed via the production of copper mandrels. Each mandrel was produced by performing multiple experiments and qualitatively and quantitatively examining the resultant depositions and the initial and final states of the experiment. The results were measured based on variations of current and voltage duration in the bath cycle, time duration, solution concentration, and change in mass of both the anode and cathode. The variables such as plating constant and direct current distribution are determined. It seems the rate at which the structure can be fabricated depends on the type of electrolytes used and the parts that are deposited can be scalable.

### **Introduction**

Electroforming is a fusion process in which a low voltage charge is passed through a medium in a concentrated premixed electrolytic bath. This breaks down the material so that metallic entities are separated from their original medium. The purpose is to fully separate metallic ions from one substance and apply them to another, as shown in Fig. 1. The deposition material is used for the anode, which is positively charged. Once charged, positive ions of the material are transferred to and deposited onto the negatively charged cathode.



Figure 1. Electroplating Setup (Kopeliovich, 2013)

The deposition rate is proportional to the current and time according to Faraday's Law, which states that the volume of the deposited substance is proportional to the current for a length of time via the plating constant. This can be shown mathematically by the formula:

in which V is the volume of metal that is plated  $(mm^3)$ , C is the plating constant based on electrochemical equivalent and density  $(mm^3/A - s)$ , I is current (A), and t is the amount of time for which current was applied (s).

The selection of electrodes and electrolytes depends upon the cell electrode potential. For copper-to-copper electrolytic cells (assumes standard 1 molar concentration),

Cu(s) | Cu2+(aq) || Cu2+(aq), Cu(s) Ecell = Eox + Ered = -0.34 V + 0.34 V = 0.0 V.

Thus it needs to be driven by a power source capable of producing a voltage. Similarly, the reaction could be spontaneous depending upon the reaction as shown below. For Zn in Cu, the reaction is spontaneous and it may not need the additional power source. Similarly, to test the spontaneous voltaic cells, the cell generates 1.10 V.

Zn(s) | Zn2+(aq) || Cu2+(aq), Cu(s)Ecell = Eox + Ered = 0.76 V + 0.34 V = 1.10 V

The electrodeposition depends upon the rate at which the positive ions from the electrolyte enter the crystal lattice and positive ions from the crystal lattice to the electrolyte. The balance between the two aid in the smooth deposition, however one rate may be faster than the other.

The objective of this research is to test the feasibility of depositing complex shapes and sizes using the electroforming process. Copper is the most electroplated metal and it has been plated on plastics, die casting parts, jewelery and automotive parts, etc. A FormLabs 2 printer, as shown in Fig. 2, was used to print precise and accurate models to the desired scale of a honeycomb structure. The printer has the capability of using a stereolithographic resin, which forms polymers when its monomers are photochemically bonded via a laser.



Figure 2. FormLabs 2 Stereolithography 3D Printer and Design

## **Methods**

One preliminary study was performed with a home-made electrolyte for 1 hour time with a 1V power supply on a non-castable resin. The results show a deposition height of 134.94  $\mu$ m as shown in Figure 3.

Pilot studies were conducted in order to determine the viability of additive manufacturing via electroforming. Two different types of electrolytes were used for the experiments. The first experimental setup utilized a home-made solution mixed from copper (II) sulfate crystals in deionized water. The other experimental setup involved using the commercially available Rio Grande Midas solution (Fig. 4). The two electrodes were kept at a fixed distance and the voltage was varied. The initial and final current was measured and the rate of deposition was observed periodically to fill the surface of the honeycomb structure.

The honeycomb model shown in Fig. 2 was a prime example of a product that has been used for simple depositions as the electrodeposition occurs primarily on the base of each hexagonal area due to gravitational effects. In addition, the surface area to volume ratio is high for a honeycomb structure. The dimensions are described in Fig. 2 and the structure is 1 mm in height.

A 200 mL beaker was used in the experiment with the copper electroforming solution. The equipment was first cleansed with deionized water and isopropyl alcohol to reduce any residual presence of resin and dirt. The corrosive acid-based solution contained 20% copper sulfate and less than 10% sulfuric acid produced industrially and primarily treats copper metal of any sort once diluted. The honeycomb structures were printed with a 1mm thickness and the cathode and anode plates were about 0.7 mm. The plates were placed on opposite sides of the beaker and the required time and current were set. The initial masses of both the anode and cathode, the initial voltage and current, and the volume of solution used were recorded. During runtime, the experiment was monitored for anomalies and records of such were kept. Once the experiment was finished, the final voltage and current were recorded and the anode and cathode were removed from the electrolytic bath and allowed to dry.



Figure 3. The surface measurement of the deposited structure using optical profilometer.

Once the experiment was set up, electrodeposition commenced. During the electrodeposition process, a current was run through two metallic plates placed in a solution containing metallic ions. These ions were deposited on one of the plates, called the mandrel. Electroforming will take this one step further. Once the plating has finished, the deposited metal will be separated from the mandrel to become its own autonomous part. This part can then be ergonomically shaped for more finely textured geometries and tighter tolerances (Precision

Eforming LLC). Sintering, the procedure to be used for deposition shaping in future experiments, involves coalescing the metallic ions by applying heat just below the liquefaction point.

The construction of the cathode involved trimming the depositing honeycomb structure and using an adhesive to gently apply it to a copper plate. The surrounding external areas were rubber coated with several layers to prevent overgrowth outside the structure. The drying period took approximately 24 hours before experimentation was to begin in order to prevent the breakdown of wet rubber coating. A similar copper plate (anode) was cut out with the same dimensions as the newly created structure but in a more thicker setting to give as much deposition as possible.



Figure 4. Midas Rio Grande Electroforming Solution

# **Results and Discussion**

The pilot study results using the home-made electrolytes can be seen in Fig. 5 and Table 1. As seen in the results, the deposition time to deposit the high structure was 24 hours. Alterations of the voltage yielded significant changes to the volume and texture of the deposition. The deposition's thickness is variant based on the voltage and current application but also depends on the placement of both anode and cathode, the volume and concentration of the electrolytic bath, environment, and temperature, etc. It can be observed that the middle two hexagonal structure (1.2 and 1.6 V) has a finer layered structure compare to outer hexagonal structures. The mandrel with 1.2 V does not display as much deposition as expected, while the

2.0 V structure carries more overgrowth on top of the structure, resembling the formation of dendrites.

The results of the experiments were promising. Most of the experiments resulted in copper deposition completely or mostly covering the exposed copper on the cathode. Increased voltage appeared to cause increased deposition rates but a rough surface texture, and growth of dendritic structure, while lower voltage yielded less deposition with a smoother surface. An overall increase in the current could have lead to insufficient ion growth and so it is unable to keep pace with the rate of electron flow which would then cause it to combine with other objects submerged within the solution. The current density is the exponential function of the overpotential [4], thus increasing higher voltage lead to unstable growth in the substrate. The exterior wall of the printed areas was the only visible material and so caused overgrowth within those areas. The surface appears non-uniform.

Concentration	Voltage (Volt)	Initial Current (Amp)	Final Current (Amp)	Distance	Time
50g/L	1.2V	.05A	.08A	2.25in (57mm)	24hrs
50g/L	1.6V	.05A	.07A	2.25in (57mm)	24hrs
50g/L	2.0V	.07A	.10A	2.25in (57mm)	24hrs

Table 1. Pilot Study using home-made electrolyte



Figure 5. Pilot Study using home-made electrolyte solution to deposit copper alloy; 1.2, 1.6 and 2.0 V respectively (24-hour runtime)



Figure 6. Commercially available electrolyte solution (1-hour Runtime)

Exp. #	Cathode Mass (Initial), (g)	Cathode Mass (Final), (g)	Overall Mass (g)	Anode Mass (Initial), (g)	Anode Mass (Final), (g)	Overall Mass (g)
1	3	3.5	0.5	3.5	3	0.5
2	3	5.5	2.5	3	2.5	0.5
3	3	7	4	3	2.5	0.5

Table 2. Parameters before and after deposition using home-made electrolyte

Exp. #	Initial Current (V)	Final Current (V)	Initial Voltage (V)	Final Voltage (V)	Distance	Duration	Volume (mL)	
1	0.19	0.28	0.7	0.7	40	1	200	C=0.5/[(8.96 x 10^-3)(0.28)(3600)] = 0.0554
2	0.65	0.18	1.5	1.5	40	1	200	C = 2.5/[(8.96 x 10^-3)(.18)(3600)] = 0.9688
3	0.29	0.54	1	1.1	40	1	200	C = 4.0/[8.96x10^-3)(.54)(3600)] = 0.2296

Table 3. Overall Parameter and Plating Constant using commercial electrolyte



Figure 7. Graph of the volume of copper deposition (cm<sup>3</sup>) versus current (A)

The overall structures from Fig. 6 shows mild deposition with the commercial electrolyte. Within 1 hr interval. At higher voltage (3.5 V), the mandrel begins to gain mass in the final product as the anode begins to lose mass and begin to rest on the bottom of the beaker. With voltage changes and constant volume, the distance between the plates, and time duration, each trial was run depending on the mass of each plating material and resulting in a corresponding plating constant. The plating constants determined from the data using commercial electrolyte is shown in Fig. 6. As seen in Fig. 6 the relationship is non-linear, this may be due to the faster rate of electron transfer from the anode to the solution than to the cathode, which leads to the disintegration of the anode.

The formations within the honeycomb yielded promising results. Based on the data collected, the variability in the value of the plating constant indicated a need for more experiments to be performed while holding other factors constant, particularly lower potential.

### **Conclusion and Future work**

Two different types of electroplating solutions were used to deposit copper inside a sacrificial mold. These solutions have a direct impact on the deposition rate. Using a home-made copper sulfate electrolyte, coarse dendritic structures have been grown. A commercial electrolyte solution has been also tested, and finer structure was formed, however, the copper electrode crumbled (disintegrated) into pieces. Determination of the plating constant (C) for copper will aid in the future use of electroforming of copper clarifying the relationship set forth by Faraday's law for the type of electrolytic solution.

Future work involves reducing the potential and increasing the time for the electroforming to obtain a finer surface.

## **References**

- "Difference Between Electroforming and Electroplating." Precision Eforming LLC. https://www.precisioneforming.com/about-electroforming/electroplating-vs-electroforming/
- Roberts, Kevin. "Electroplating: Materials Science Research Project" WordPress.com. .https://exoticsteel.wordpress.com/theory/.

Fig. 1, Kopeliovich, Dmitri. "Electroplating" *Substances and Technology*. SubsTech.com 14 Dec. 2013., http://www.substech.com/dokuwiki/doku.php?id=electroplating

Schlesinger, M., & Paunovic, M. (Eds.). (2011). *Modern electroplating* (Vol. 55). John Wiley & Sons.