# SIMULATION OF NICKEL ELECTROFORMING PROCESS OF A REVOLVING PART USING FINITE ELEMENT METHOD

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***Abstract:*** *In this paper a finite element model has been proposed for evaluation of primary and secondary current density values on the cathode surface in nickel electroplating operation of a revolving part. In addition, the capability of presented electroplating simulation has been investigated in order to describe the electroplated thickness of the nickel sulfate solution. Nickel electroplating experiments have been carried out. A good agreement between the simulated and experimental results was found. Also the results showed that primary current density can describe the general form of thickness distribution but the relative value of current density using secondary current density can present better description of thickness distribution.*

***Keywords:*** *Nickel electroforming, finite element simulation, Thickness distribution, Primary current density, Secondary current density*

## 1. INTRODUCTION

Electro deposition is one of the most important processes in the field of industry. Still this historical coating process is the most dominant manufacturing technology in many new applications. Electroforming process is a specialized use of electroplating for manufacturing metal and composite parts. In this process a metal layer is electrodeposited upon a cathode or mandrel. This process has the capability to manufacture a wide range of products from consumer products to aerospace components. Also it can be used to produce machinery, electronic and automotive parts (McGeough, J. A. et al., 2001). It is well known that one of the major problem of this process is to obtain a uniform thickness distribution on the mandrel surface with a curved shape (McGeough, J. A. et al., 2001).

During the years, researchers in the field of electroplating and electroforming always tried to predict the thickness of coatings deposited on the parts or mandrels. Mathematical modeling has been used to describe the electroplating process. One of the first models was introduced by McGeough and Rasmussent (J. A. McGeough, H. R., 1976). They used perturbation analysis to find a model to achieve more uniform thickness distribution on a mandrel surface with sinusoidal mandrel surface with irregularities. Also they analyzed electroforming process with direct current by perturbation method (J. A. McGeough, H. R., 1977; 1981). The mathematical model was limited to simple model shapes of cathode and anode.

By using numerical methods such as finite element analysis (FEA) one can simulate more complex shapes and conditions compared to analytical modeling, as this method used for modeling other processes like corrosion and casting (Azizi, A. et al., ; Jafaria, A. et al.). Some researchers have been used FEA for electroplating process simulation. Yang et al. (Yang, J. M. et al., 2008) simulated primary current density of nickel electroplating process and compared its values with relative thickness. Also Zhu et al. (Zhu, Z. W. et al., 2008) applied primary current density FE simulation on the cathode surface of near-polished surface of nickel. They showed that the simulated current density curve is similar to relative thickness curve. Masuku et al. (Masuku, E. S. et al., 2002) used 2D and 3D finite element analysis to determine the local plating depth for copper plating process. They found that 3D model has a





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good agreement with profile of the real plated surface. A model of current distribution and electrode shape change for electro deposition in the presence of diffusion controlled leveling agents was developed by Dukovic and Tobias (Dukovic, J. O. & Tobias, C. W., 1990). The solution was obtained by the boundary element method, with a flexible moving boundary algorithm for simulating the advancement of the electrode profile. The profile was predicted during deposition and compared with measurements. Li et al. (Li, X. et al., 2007) were developed a multi scale simulation model to simulate shape evolution during copper electro deposition in the presence of additives. The model dynamically was coupled a kinetic Monte Carlo (KMC) model with a finite volume (FV) model. Numerical results include predictions of the surface concentration distributions as a function of time and distance was reported. A novel micro electroforming process, which targets the cost efficient fabrication of high-aspect-ratio metallic microstructures, was presented by Zhu and Zeng (Zhu, D. & Zeng, Y. B., 2008). Typical high-aspect-ratio metallic micro parts in the scale of several hundred microns were produced and the current density distribution and metal deposition in the proposed process were studied.

Generally, making a precise model for thickness distribution during the electroplating and electro forming process is the key point of all scientific actions, as noted above. The success of electrodeposition in electronics and other industries has depended largely upon efforts to achieve uniform films of a metal. In this research after conducting electroplating experiments, the coating thickness of different points was measured. Primary and secondary current density was simulated using the commercial FE software code COMSOL and the relative value of thickness and current density compared with each other.

## 2. ELECTROPLATING THEORY

In electroplating process, the deposited thickness distribution and other properties like surface texture and morphology are directly related to current distribution (Dukovic, J. O., 1990). Current distribution can be analyzed in two different macro and micro scale. Macroscopic scale is about solving models on the order of centimeter and is to analyze thickness distribution. Micro scale is about sub millimeter length scale and is to analyze deposit texture and roughness, nucleation.

Based of Faraday's law in electrochemistry, if we find the current density value on different points on cathode surface, we can predict the deposited metal layer (Mario, M. et al., 2008). In this paper the macroscopic current density distribution was studied.

There are some simplifying approximations for electroplating simulation. Primary, secondary, mass transport and tertiary current density are common approximations for modeling the current distribution. Because in this article we study the primary and secondary current density distribution for nickel electroplating process, so in following sub sections we introduce these two kinds of approximations.

### 2. 1. Primary Current Density

Base on Newman theory, the potential $V$, obeys Laplace equation in the electrolyte.

$$\nabla^2 V = 0 \tag{1}$$

In the boundary condition at all insulting boundary or symmetry plane is

$$\frac{\partial V}{\partial \vec{n}} = 0 \tag{2}$$

Where $n$ is a unit vector normal to the surface. In this kind of approximation just Ohmic irregularities was considered kinetic and mass transport limitations was neglected.

### 2. 2. Secondary Distribution

If we considered both, Ohmic and Kinetic irreversibility, the simulated current called





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secondary current density. In this kind of approximation the mass transport limitation was neglected.

In this condition Laplace equation will solve with following boundary condition

Insulator:

$$\frac{\partial V}{\partial n} = 0 \tag{3}$$

Cathode surface:

$$V = V_E - \eta s \tag{4}$$

Where $\eta s$ and $i$ is relate to each other by Tafel equation

$$\eta s = A_c \times \log\left(\frac{i_{loc}}{i_o}\right) \tag{5}$$

Where $A_c$ is the slope of Tafel line. $i_{loc}$ is local current density, $i_o$ exchange current density (Dukovic, J. O., 1990).

**Table 1.** Electrolyte composition

| | |
|---|---|
| Nickel sulfate | 220 (gr / Lit) |
| Nickel Chloride | 30 (gr / Lit) |
| Boric Acid | 30 (gr / Lit) |
| pH | 3.5 |

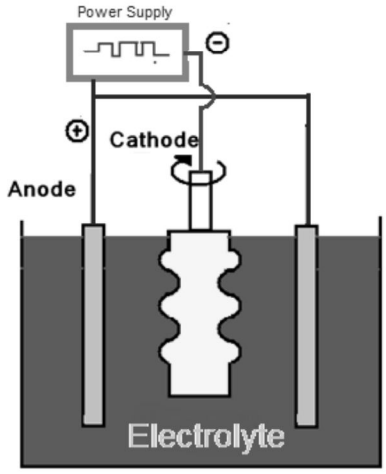


**Fig. 1.** A schematic diagram of electroforming System

## 3. EXPERIMENTAL PROCEDURE

Fig 1. shows a schematic diagram of the electroplating system used in this research. This system has a rolled rounded nickel anode and cylindrical aluminum mandrel. The nickel sulfate solution was used as the electrolyte. Its composition is shown in Table 1.

The plating process was conducted using direct current (2 Volts). The temperature was fixed at 55 ºc and a good electrolyte perturbation was used. The cell dimensions were 15×15×15 cm³. The volume of electroplating cell was about 3.4 L.

Aluminum mandrel with a complex cylindrical shape was degreased with organic solvent and rinsed. After plating process the sample was cut from its central axis with WEDM (Wire Electro

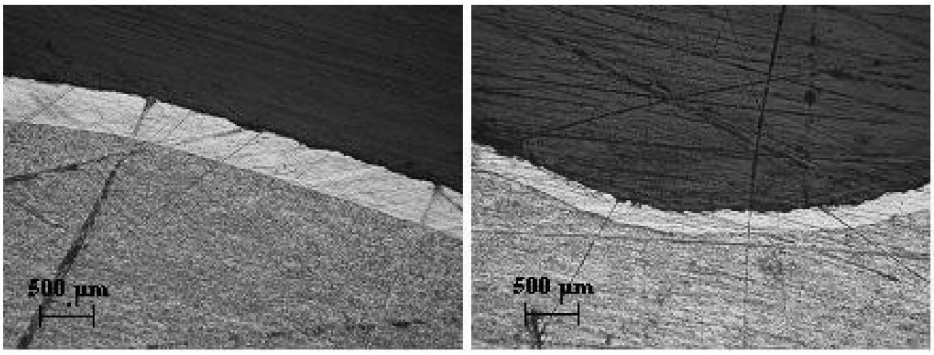


**Fig. 2.** Electroplated sample





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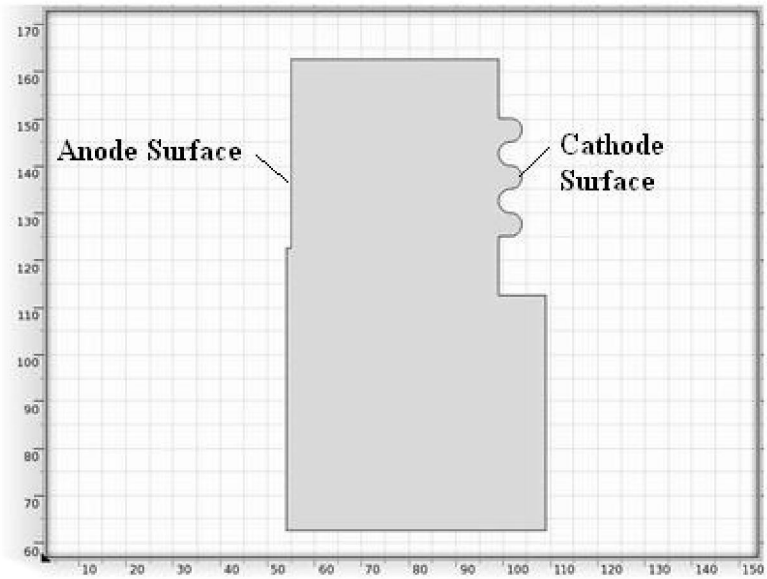


**Fig. 3.** Defined geometry for finite element simulation

Discharge Machining). Sample was mounted polished and thickness was measured using optical microscope (Fig. 2).

## 4. FINITE ELEMENT MODEL

The Finite Element Method (FEM) is a numerical method for solving differential and integral equations. In this method, the unknown variables to be determined are approximated by piecewise continuous functions. The coefficients of the functions are adjusted in such a manner that the error in the solution is minimized. Usually, the coefficients of the functions of a particular element are the values at certain points in the element called nodes. During the solution process, the differential equations get converted to algebraic equations or ordinary differential equations that can be solved by finite difference equations. The finite element method consists of

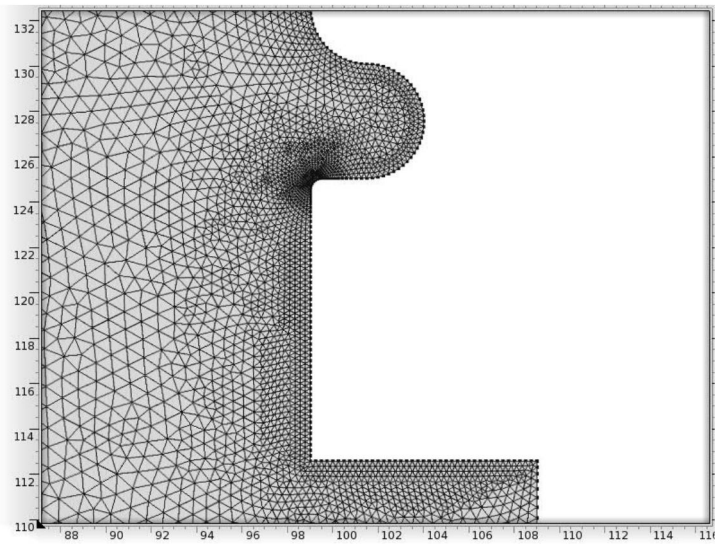

**Fig. 4.** Applied 2 dimensional elements for simulation





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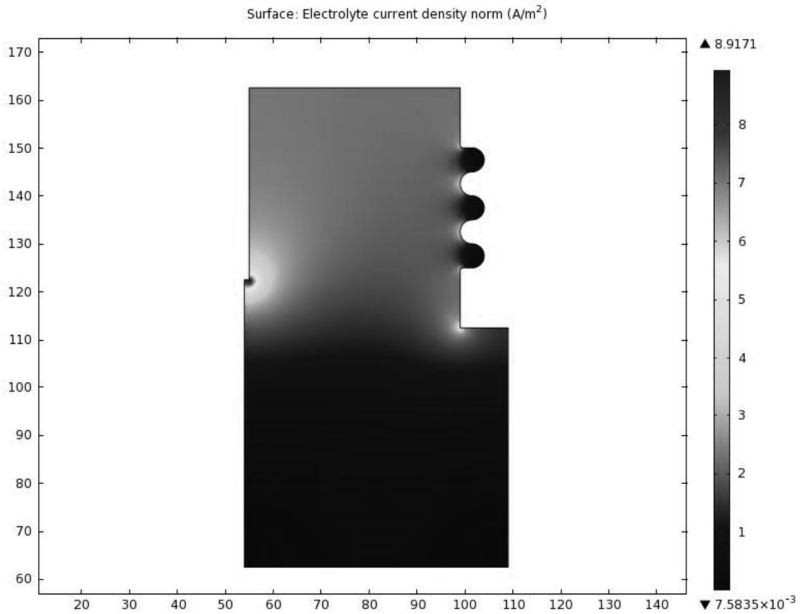


**Fig. 5.** Simulated Current Density in electrolyte

the following steps: (i) Pre-processing; (ii) Developing elemental equations; (iii) Assembling equation; (iv) Applying boundary conditions; (v) Solving the system of equations; and (v) Post-processing.

A FE numerical model was developed for electroplating simulation. A 2D geometric model of anode and cathode surface and also electrolyte was constructed. Defined geometry for finite element simulation is shown in Fig. 3. Geometry was defined by key points, lines and curves to define an area that electroplating process happens in it.

To define cathode, anode and electrolyte a value of electrical conductivity and electrical voltage was applied. Also for simulating secondary current density, surface kinetic was applied to the cathode surface using Tafel equation. FreeQuad was selected as the element type. The element size and total number of elements were 23000 and 0.5 mm, respectively. After conducting preprocess phase of FE model, the defined finite element model passed for the solution. An applied 2D element for simulation is shown in Fig. 4.

During the FE solution, solver yields the potential and current density on each node. The value of primary and secondary current density was extracted in the points that their thickness was measured before. Fig 5 shows the simulated current density in electrolyte. 3D graph of simulated current density is illustrated in Fig. 6.

For validation of electroplating simulation, researchers (Yang, J. M. et al., 2008; Zhu, D. & Zeng, Y. B., 2008; Zhu, Z. W. et al., 2008) compare the relative thickness values with the relative current density instead of direct calculation of thickness using simulated current density.

## 5. COMPARISON OF RESULTS

In Fig. 7, the relative value of thickness compared with relative value of primary and secondary current density. Relative value is defined as follow.

$$T_k = \frac{t_k}{\left(\frac{1}{n}\sum_{k=1}^{n} t_k\right)}, t_k = 1 \sim n \tag{6}$$

Where the number of measured value is, is the value (thickness or current density) at the selected position.

According to Fig. 7, all three curves show the same profile trend. At the points with higher diameter more thickness was deposited and also in comparison with other points, the simulated





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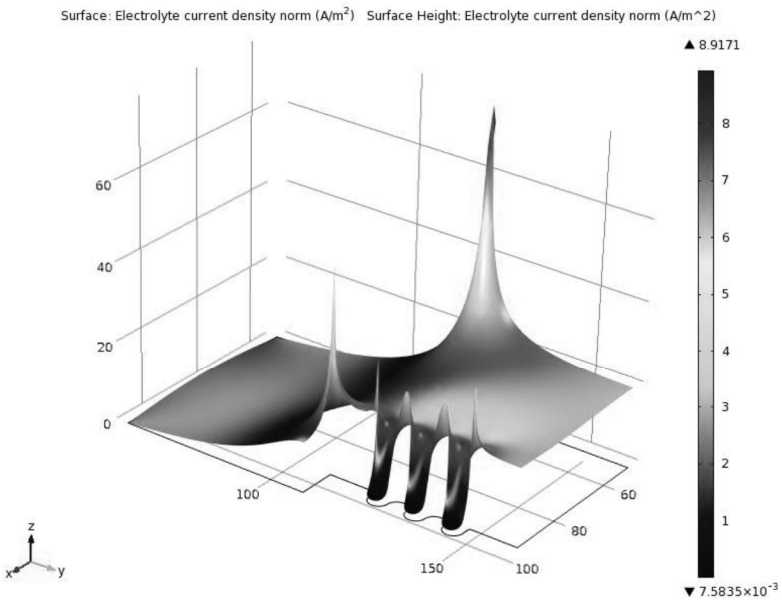


**Fig. 6.** 3 Dimensional Graph of simulated current Density

primary and secondary current density have higher relative value.

However the actual divergence between measured thickness and simulated current density, at the edge of mandrel is increased compared with other points.

Also it can be described that relative value of simulated secondary current density has a better agreement with relative thickness value compared with relative value of simulated primary current density. After applying surface kinetic boundary condition by use of Tafel equation, maximum value of simulated primary current density was decreased and minimum

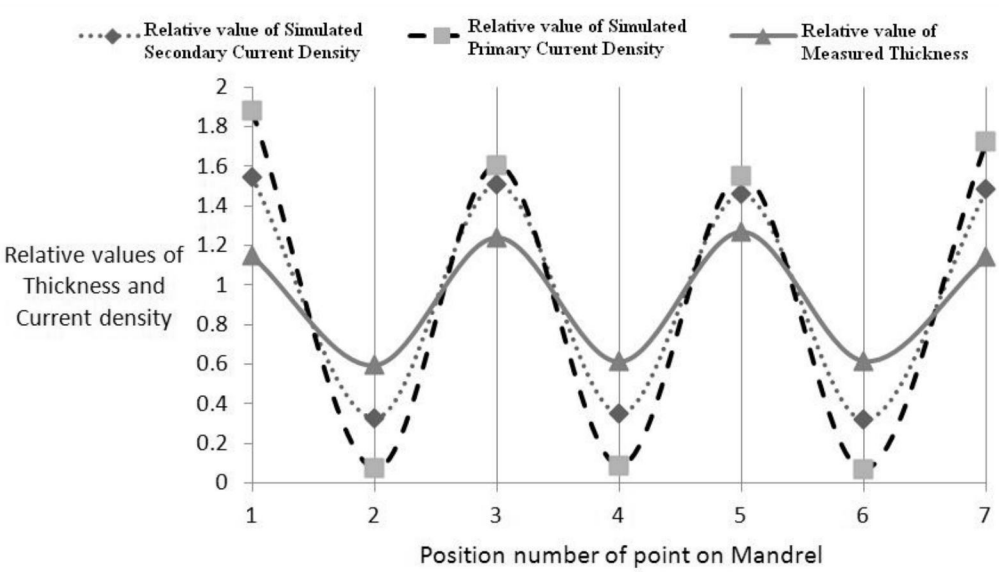


**Fig. 7.** Comparison of results





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value was increased. It shows that the primary current density has a major effect on thickness distribution in nickel electroplating process, but by applying surface kinetic limitation on finite element model, the thickness distribution can be described with more precision. In Fig 7 the high current density points, is represent the convex points on the mandrel that have the lowest distance between anode and cathode. On the other hand, convex points have the lower current density and thickness because of higher distance between anode and cathode. Base on the generated Finite Element model, current density valve could compute for the each point on the cathode (mandrel).

## 6. CONCLUSION

An experimentally supported 2D finite element simulation of the nickel electroplating process was presented in this paper. The relative values of thickness, primary and secondary current density, obtained from simulation, were compared to those of experiments. The general profile of the real plated thickness has the exact behavior with simulated current density. When the thickness increase at the points with the higher diameter, the simulated current density increase relatively. Also lower thickness at the low diameter points, face with decrease in simulated current density. Also it was shown that the secondary current density distribution has a better agreement with relative thickness distribution in nickel electroplating with nickel sulfate solution.

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