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Printed Circuit Boards Manufacturing using Electrodeposition Process: An Innovative Numerical Model

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Abstract - *Electroforming* stands as a vital and cost-effective method widely employed not only to mitigate corrosion but also to improve the aesthetic appeal of various products. Through the process of Electrodeposition, a fine layer of the desired metal is meticulously deposited onto a base object, creating a unified and durable coat that not only supports against corrosion but also imparts an exquisite finish, elevating the overall quality and visual allure of the item. In this paper, we propose *an innovative modeling approach to simulate Printed Circuit Boards* (PCB) *manufacturing*, based on *metal Electrodeposition* using the commercial software *COMSOL Multiphysics: Electrodeposition Module*. In order to ensure the robustness of our numerical model, we undertake a systematic exploration by investigating the impact of various process parameters on the weight and thickness of the electrodeposited metal.

Keywords: Electroforming, Copper Electrodeposition, Printed Circuit Boards, COMSOL Multiphysics.

1. Introduction

Nowadays, Electrodeposition, an *electroforming process* that is akin to *electroplating*, emerges as an interesting research area that has been widely used in the field of electroforming (e.g., [1-3]). Electroforming, also known as electrochemical forming, is widely considered a *sustainable* and additive manufacturing process. This process can be used in extensive applications across diverse domains, such as *electronics*, *metallurgy*, *automotive*, *biomedical fields*, and so forth (e.g., [4,5]). Moreover, the Electrodeposition process enables the creation of tailored decorative and anti-corrosion coatings with precise thickness, composition, and properties, as well as high-precision passive electromagnetic cloaking devices for nanotechnology. As a result, this methodology is prominent for its ability to produce precise and thorough data.

Moritz Hermann von Jacobi, a Prussian engineer and physicist, was the first to develop electroforming as a technical procedure in 1838. Since then, the method has been used in a variety of applications, ranging from the manufacture of micro-components for the medical and electronics sectors to the building of huge parts for the aerospace industries, so influencing our daily lives. The electroforming process has been a subject of interest for several decades. The initial numerical investigations of the process came forth during the 1970s. Electroforming has only been sporadically studied since then, in conjunction with the rapid advancements in computational sciences (e.g., [6]). On the other hand, there has been a recent surge in interest in this process, its applications, and the ability to model it with greater rigor. Specifically, electroforming induces deformation on the surface of the reaction, and modeling these deformations can pose challenges (e.g., [7-9]). In the meantime, there have been more experimental studies of this process.

Additionally, for what concerns the Electrodeposition process, it necessitates the use of two electrodes, namely an *anode* and a *cathode*, which are immersed in a conductive electrolyte that contains metallic salts along with a *DC power source*. As the current is passed between the two electrodes, metallic ions, such as Ni++ or Cu++, present in the solution are transformed into atoms on the surface of the cathode. These atoms accumulate layer upon layer, micron upon micron, resulting in the formation of an uninterrupted deposit, which is the focus of our research.

Indeed, Electrodeposition serves as a crucial method for creating key components, notably *Printed Circuit Boards* (PCB). These PCBs primarily consist of non-metallic materials like *plastics*, *fibers*, and *ceramics*, accounting for approximately 70% of their composition, alongside metals like *Copper*, *Nickel*, *Gold*, and *Tin*. While the composition of

PCBs may differ based on factors like their age, origin, and manufacturer, *Copper* stands out as one of the most abundant metals consistently found in these PCBs [10,11].

Following these considerations, in this paper, our main contribution consists of proposing *an innovative numerical model to investigate Printed Circuit Board manufacturing based on metal Electrodeposition using the commercial software COMSOL Multiphysics: Electrodeposition Module*. Overall, in this paper, we made the following contributions:

- we initiate by presenting a comprehensive overview of the context, background, and motivation that inspired us to conduct this research;
- we also provide a state-of-the-art analysis, which allows us to provide a comprehensive vision of the recent and pertinent work related to our research;
- we illustrate the fundamental principle of the Electrodeposition process, as well as introducing the essential mathematical models and also the geometry and parameters of our numerical investigation;
- we conduct a rigorous numerical assessment and analysis of the effect and impact of the electrodeposited material nature and the applied potential in order to ensure the effectiveness and reliability of the proposed numerical model in handling the Electrodeposition process.

The remaining part of this paper is organized as follows. Section 2 focuses the attention on analyzing relevant related work to our research. In Section 3, we present the fundamental principles of the Electrodeposition process and mathematical models. After that, in Section 4, we report our extensive applications and the results obtained. Finally, Section 5 provides conclusions and possible future work for our research.

2. Related Work

In this Section, we highlight some of the most relevant and pertinent related work that appeared in the active literature.

[12] highlights the development and challenges faced in creating dynamic windows using *Reversible Metal Electrodeposition* (RME) technology. These windows can electronically adjust light transmission, thereby enhancing both building aesthetics and energy efficiency by controlling the flow of light and heat. Specifically, they discuss RME devices using *Copper* (Cu) and *Bismuth* (Bi) to achieve different levels of light transmission. Interestingly, electrodeposited Bi films exhibit compressive stress, likely due to high self-diffusion and atomic insertion into grain boundaries during plating. This unique property results in Bi-based dynamic windows that remain crack-free during resting periods, providing stable functionality for over 9 weeks. Finally, the contribution underscores the challenges faced in achieving stable and functional dynamic windows using RME technology, with insights into the mechanical failures encountered with Cu–Bi films and the contrasting stability achieved with Bi-based films.

[13] describes the successful creation and assessment of *Graphene Oxide/HydroxyApatite* (GO/HA) composite coatings on a titanium substrate using *electrophoretic deposition technology*. Detailed evaluations encompassing microstructure, phase composition, adhesion strength, corrosion resistance, bioactivity, hydrophilicity, antibacterial activity, and biocompatibility were conducted. Remarkably, the incorporation of GO significantly enhanced the adhesion strength of the coatings while also minimizing the corrosion rate. The composite coatings exhibited excellent bioactivity in biomineralization experiments and demonstrated increased hydrophilicity as the water contact angle increased. Overall, this research highlights the successful fabrication of GO/HA composite coatings with enhanced adhesion strength, corrosion resistance, bioactivity, altered surface hydrophilicity, antibacterial properties, and good biocompatibility. These findings hold promise for various biomedical or biomaterial applications.

In [14], they present an innovative method for extracting Copper from ground and concentrated PCB powder. The innovative process involves anodic dissolution of a powder sample containing approximately 48% Copper and 40% other metals, along with 12% non-metallic materials, in an acidic Copper sulfate solution. Simultaneously, Copper ions are reduced on the cathode, resulting in the production of pure electrolytic Copper and a solid residue rich in tin, lead, non-metallic materials, and minimal Copper content. Key findings highlight the influence of agitation and temperature on Copper recovery, with agitation identified as the paramount factor in enhancing efficiency. *Scanning electron microscopy* (SEM) and *energy dispersive spectroscopy* (EDS) analyses confirmed that the recovered Copper from PCBs contained negligible impurities, positioning this process as a promising alternative for Copper recovery.

The purpose of [15] is to optimize parameters for high-density interconnections in PCBs using a *Rotating Disc Electrode* (RDE) model for Copper electrodeposition. The research aims to bridge theoretical and experimental insights into non-uniform Copper deposition. An *electrochemical model* describing Copper electrodeposition kinetics on an RDE is introduced, connecting theoretical understanding with practical applications in PCB manufacturing. Utilizing COMSOL Multiphysics, the study models flow fields, potential distributions, and current distributions, aligning with theoretical predictions. Investigating fluid flow's impact on plating layer thickness and current density distribution reveals crucial aspects of PCB production. This integration helps control plating layer uniformity by studying concentration boundary layers. This platform enables accurate analysis, linking current density distribution, plating thickness, and controlled parameters, deepening our grasp of Copper electrodeposition mechanisms in PCB manufacturing.

3. Numerical Modeling of Electrodeposition Process

In this Section, we present the fundamental principles of the electrodeposition process. As well as introducing the essential mathematical models. Moreover, we also delve into the presentation of our device structure and geometrical model.

3.1. Fundamental Principles of Electrodeposition Process

Electrodeposition is an *electrochemical procedure* that uses another substance to coat a substrate. This adaptable method is utilized for both decorative and utilitarian purposes and can be found in a wide range of industries, including *electronics*, *mining*, and *nanotechnology*. An emerging employment of electrodeposition consists of producing printed circuit boards. PCBs are typically made up of one or more Copper layers placed on or between non-conductive substrates. Copper layers are divided into conductive lines or tracks, which allow signals to travel across the PCB. To create these patterned lines, Copper or other conductive material can be electro-deposited in trenches on the PCB.

Nevertheless, the use of electrodeposition for the manufacture of PCBs presents some challenges, such as the changes in the Copper coating rate on the surface of the printed circuit, which can cause performance problems and even device failure. As a result, modeling is useful for identifying and preventing difficulties with the electrodeposition process. Thereby, Equation (1) presents the *Nernst-Planck equation* [16], which describes the movement of each ion in the electrolyte as:

$$N_i = -D_i \nabla c_i - z_i u_i \, F c_i \nabla \phi_i \tag{1}$$

where N_i is the transport vector, D_i represents the diffusion coefficient, c_i is the concentration of i ions in the electrolyte, z_i is the charge for ionic species, u_i is the mobility of loaded species i, ϕ_i the potential in the electrolyte, and F is the *Faraday constant* defined as $F = 96485{,}338\ [C/mol]$.

Moreover, the material balances are expressed by Equation (2). However, for each species $i = 1.2$, the *criterion of electrical neutrality* is stated by Equation (3):

$$\frac{\partial c_i}{\partial t} + \nabla . N_i = 0 \tag{2}$$

$$\sum_i \quad z_i c_i \ = 0 \tag{3}$$

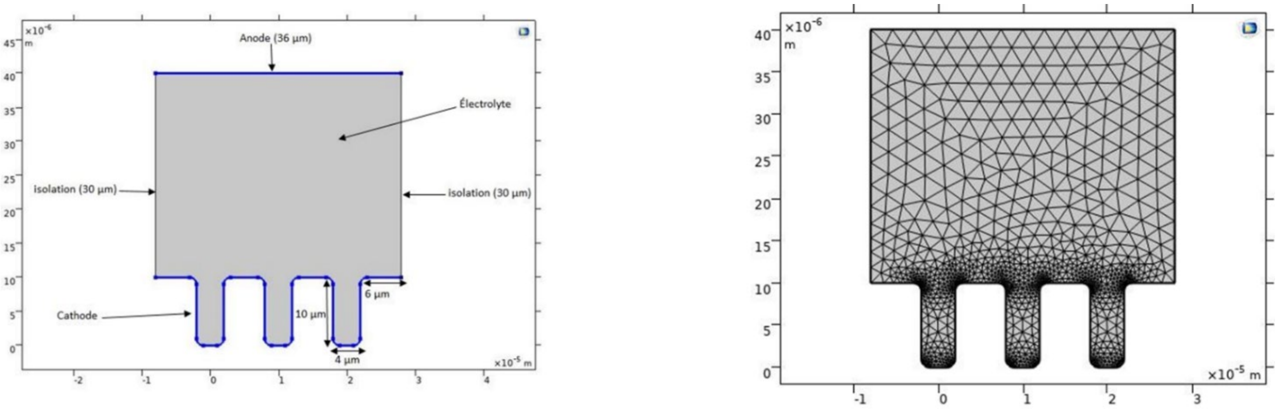
3.2. Device Structure and Geometrical Model

In this research, we attempt to represent Copper electrodeposition on a microstructure, which is a printed circuit board with three small tranches or three micro-cavities. In this application, an anode and a cathode comprise the potentiostatic plaster cell. When deposited, the cathode and anode borders move, making the simulation intrinsically time-dependent. Furthermore, the rate of Copper deposit on the cathode surface is not uniform. This application, which is based on an electrodeposition benchmark model [17], employs the COMSOL software Electrodeposition module. The use of deforming geometry allows for the analysis of the coating process as well as the investigation of the variation of the cathode boundary during the electrodeposition process.

Figure 1 (*a*) depicts the geometric model of our research, which contains the anode and cathode. The anode and cathode constitute the horizontal borders of the cell containing the electrolyte. The potentials of ±0.1V are applied at the electrode level; on the other hand, the vertical walls indicate the pattern on the primary electrode, which is presented in Equation (4):

$$-n.i_l = 0 \qquad -n.i_s = 0 \tag{4}$$

Furthermore, the mesh employed in this work represents an *automated refinement mesh* with 2167 domain nodes and 221 border elements, as presented in Figure 1 (*b*).



(*a*) (*b*)

Fig. 1: Geometric Model (*a*) and Finite Element Meshing (*b*).

4. Results and Discussion

In this Section, we present our extensive numerical assessments conducted using the electrodeposition process. Through this rigorous evaluation, we aim to demonstrate and substantiate both the effectiveness and efficiency of our numerical model. In order to realize this assessment, we delve into the evaluation of the significant impact and influence of Copper and Nickel two materials commonly used in this process, as well as the effect of voltage provided to electrodes on Copper electrodeposition.

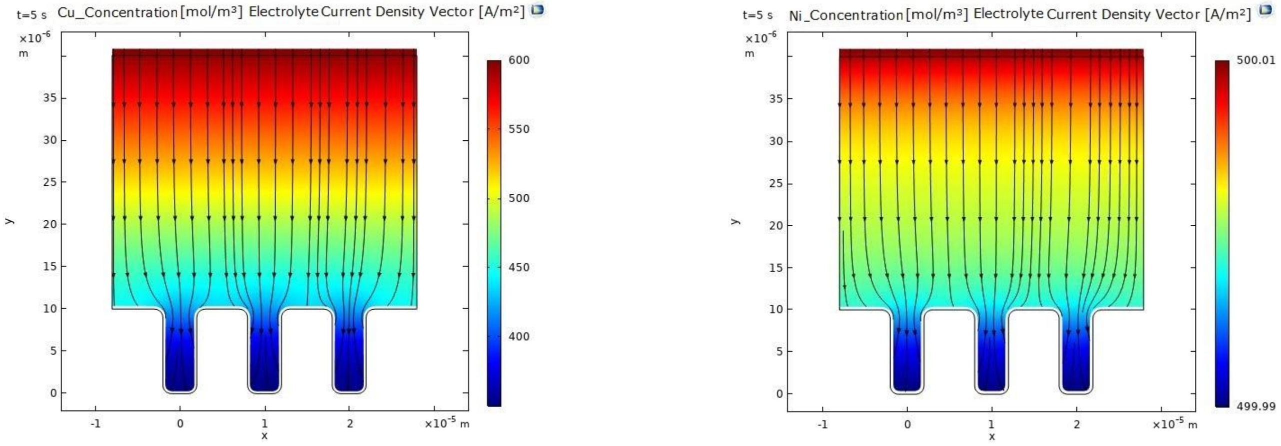
Table 1: System Parameters

Parameter	Symbol	Value	Parameter	Symbol	Value
Initial Concentration [mol/m^3]	C_{init}	500	Cu Diffusivity [m^2/s]	D_{Cu}	2.10^{-9}
System Temperature [K]	T_0	298	SO4 Diffusivity [m^2/s]	D_{SO4}	2.10^{-9}
Exchange Current Density [A/m^2]	i_0ref	250	Cu Density [Kg/m^3]	ρ_{Cu}	8960
Anode Potential [V]	φ_{anode}	0.1	Cu Molar Mass [Kg/mol]	M_{Cu}	0.06355
Cathode Potential [V]	$\varphi_{cathode}$	-0.1	Ni Charge	z_{Ni}	2
Symmetry Factor	α_a	1.5	H Charge	z_H	-2
Cu Charge	z_{Cu}	2	Ni Diffusivity [m^2/s]	D_{Ni}	$2,3.10^{-5}$
SO4 Charge	z_{SO4}	-2	H Diffusivity [m^2/s]	D_H	$4,9.10^{-12}$

4.1. Effect of the Electrodeposited Material

In this first printed circuit electrodeposition application, we studied the influence of two materials that are commonly employed in this process, i.e., *Copper* and *Nickel*. As a result, two distinct electrolytes are considered: CuSO4 and NiOH. Table 1 covers all of the parameters and limit conditions used in our extensive applications of Copper and Nickel electrodepositions.

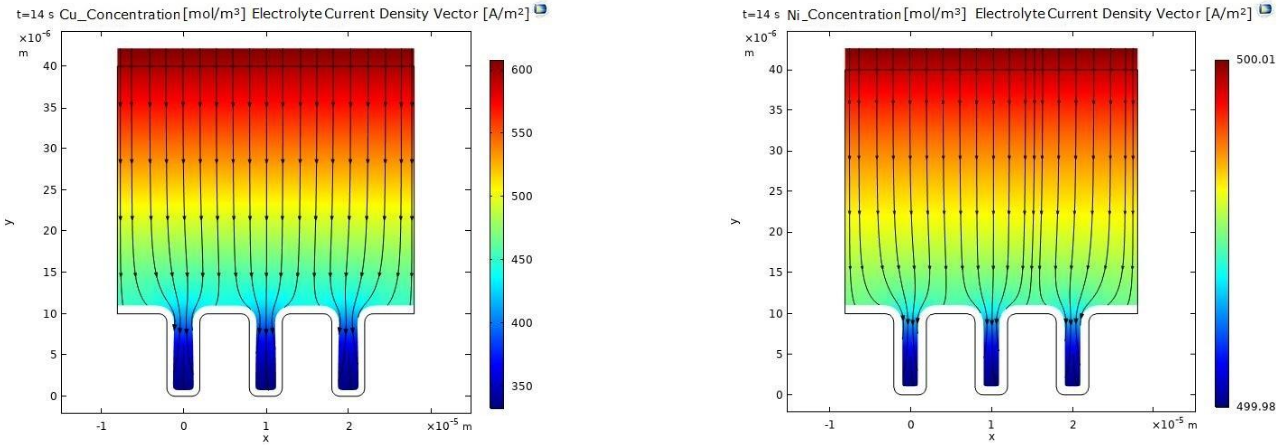
Furthermore, the Copper deposition process is examined after 5s. At this stage, the concentration of Cu ions varies greatly across the cell; it is higher at the anode and progressively declines towards the cathode (see Figure 2 (*a*)). However, the concentration of Ni ions in the electrolyte between the anode and the cathode is almost uniform (Figure 2 (*b*)).



(*a*) (*b*)

Fig. 2: Ion Concentration of Deposited Material - Electrolyte Current Density Vectors for Copper (*a*) and Nickel (*b*) at $t = 5s$.

The vectors of the electrolyte's current density are oriented from the anode to the cathode and do not differ significantly between the two situations (i.e., Copper or Nickel). On the other hand, we can see that the trench opening begins to shrink, which is caused by an increase in deposit thickness, which is uneven in the case of Copper. However, in the case of Nickel, the narrowing of the microcavity is uniform due to the homogeneity of the Nickel-deposited layer, as shown in Figure 2.

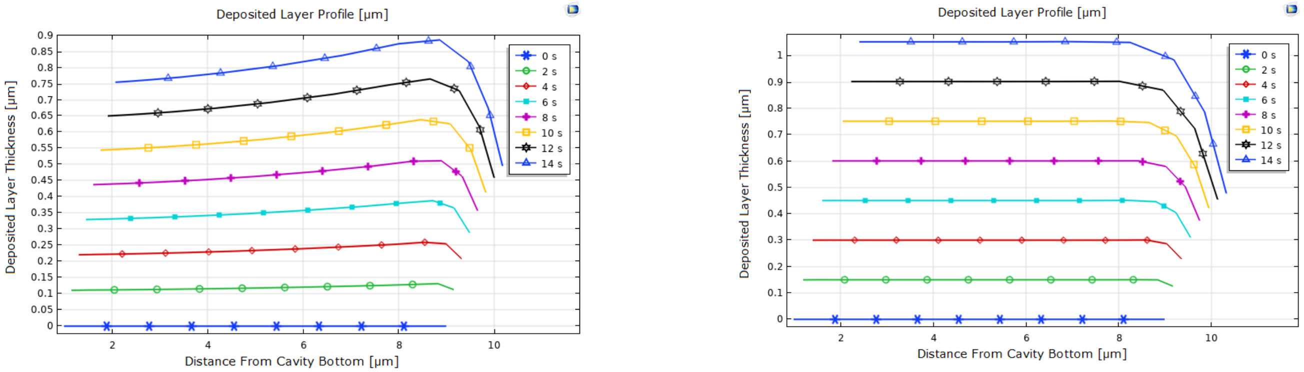


(*a*) (*b*)

Fig. 3: Ion Concentration of Deposited Material - Electrolyte Current Density Vectors for Copper (*a*) and Nickel (*b*) at $t = 14s$.

In another investigation, we increased the calculation duration to $t = 14s$, which allowed us to see thicker layers of deposit and more acute microcavity narrowing, as presented in Figure 3, both of which are theoretically supported.

Moreover, the thickness of the deposited Copper layer along a vertical cathodic surface is examined in Figure 4 (*a*). This diagram depicts an uneven deposit growing in a different way. This is caused by an uneven distribution of current density, which is exacerbated by Copper ion exhaustion along the cavity's depth.



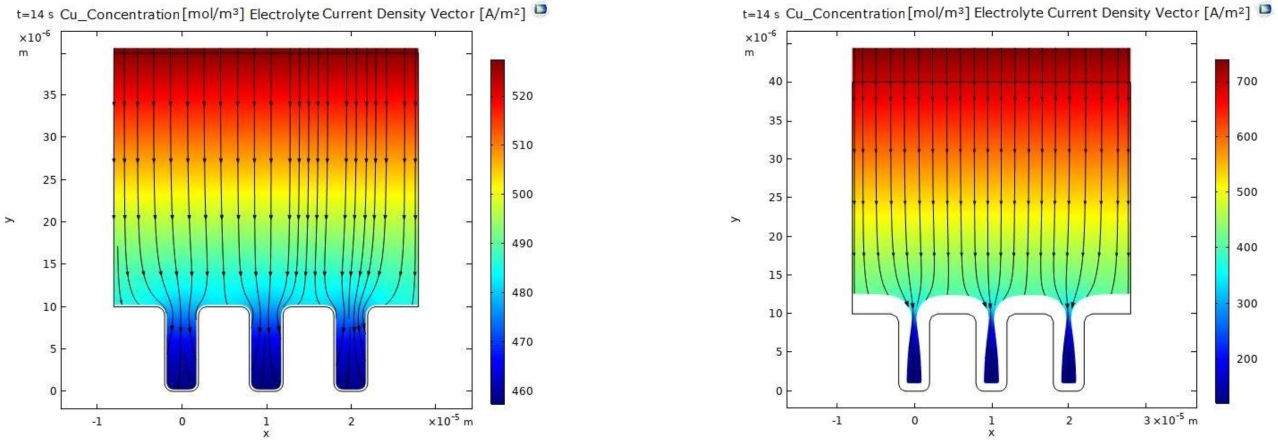
(*a*) (*b*)

Fig.4: Thickness of the Deposited Layer at Various Times for Copper (*a*) and Nickel (*b*).

However, when we compare the varied profiles of the layer deposited at the cathode level for Copper and Nickel, acquired from 0s to 14s with a step of 2s, we can clearly see that the deposit is greater in the case of Nickel, but it is well uniform except at the level of the cathode edge (see Figure 4 (*b*)). In fact, it is noteworthy that all these numerical results are validated by the electrodeposition benchmark model [17].

4.2. Effect of applied potential

In this second application, we sought to investigate the influence of voltage provided to electrodes on Copper electrodeposition. In order to realize this, we considered two cases, one with a lower potential than the previous one and another with a higher potential ($\phi = 0.05V$ and $\phi = 0.135V$). The obtained results reveal that the potential has a considerable effect on this electrodeposition phenomenon.



(*a*) $\phi = 0.05V$ (*b*) $\phi = 0.135V$

Fig.5: Ion Concentration of Deposited Copper - Electrolyte Current Density Vectors at $t = 14s$.

Indeed, changes in Copper ion concentration in the electrolyte are significantly related to potential, and the Copper layer deposited at $t = 14s$ is obviously substantial in the case of the highest potential $\phi = 0.135V$ and becomes insignificant in the case of the lowest potential $\phi = 0.05V$, as presented in Figure 5.

On the other hand, the profiles of Copper layers formed at the cathode level varied greatly for the three distinct potential levels. In the presence of important potential, the thickness of the deposited layer and the non-uniformity of the deposit are significantly enhanced, which is clearly depicted in Figure 6.

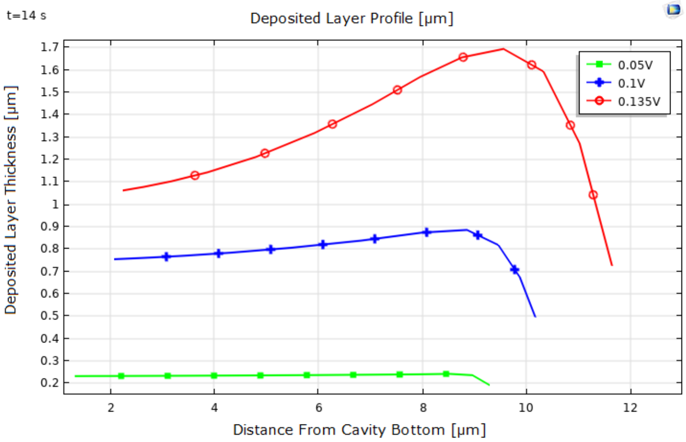


Fig.6: Deposited Layer Thickness for Different Potentials.

In summary, the obtained numerical results reveal that electrodeposition is strongly dependent on both the nature of the material deposited and the potential applied. In theory, these effects are predicted due to the fact that electrodeposition is based on electrochemical reactions, and thus the type of ions involved, as well as the potential supplied to the electrodes, constitute crucial factors. All prior numerical outcomes are reasonable and theoretically predictable. Furthermore, they have good qualitative consistency with earlier studies from the active literature.

5. Conclusions and Future Work

In this work, the production of printed circuit boards using the electroforming process is simulated and modeled, using the COMSOL software package. This innovative numerical model allowed us to perform metal electrodeposition in tranches of printed circuit boards while also investigating the effect of electrodeposited material and its applied potential. A noteworthy conclusion can be drawn from this work, that Copper and Nickel represent the most appropriate materials used in this procedure due to their behavior as conductive electrolytes. On the other hand, Nickel appears to be the most promising metal due to its greater and more uniform deposit. Moreover, electrical magnitudes such as potential and current have a significant impact on the rate of deposition and its uniformity.

As future work and by expanding our research, further study can be conducted to gain a thorough understanding of the process dynamics and to conduct more specific investigations on many aspects of this process, such as *functionality* and *efficacy*, as well as investigating other *emerging forming trends* (e.g., [18-21]).

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