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Computer Aided Electroforming. Elecform3D™.

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Abstract

Electroforming is an electrolytic process that enables the manufacture of metallic parts with good mechanical properties and a high level of accuracy and reproducibility. In this process a thin metallic shell is deposited onto a model part and later released from it. However the two main disadvantages of electroforming are the non-uniform thickness distribution and the high time of processing. Procesos de Fabricación research group, of the University of Las Palmas de Gran Canaria (ULPGC), has been working in the electroforming process and its applications focused on rapid manufacturing techniques, for the last twelve years. Elecform3D™ product is an innovative numerical analysis and simulation tool of electroforming process, based on the boundary elements method, which aims to facilitate design and manufacturing tasks for metallic shells production. This product work enables better thickness uniformity as well as lower time manufacturing, achieving High Speed Electroforming therefore enabling new application fields.

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1. Introduction

More than twelve years ago *Procesos de Fabricación* Research Group of the University of Las Palmas de Gran Canaria, after analyzing the different solutions in the area of Rapid Tooling, the study of a not very widespread technique, the electroforming process was proposed. According to the definition adopted by ASTM (B832-93:

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Standard Guide for Electroforming with Nickel and Copper), "electroforming is the production or reproduction of articles by electrodeposition upon a mandrel or model part, which is then separated from the metal shell".

This was the origin of several research activities focused on the application of electroforming as a complementary technique of Rapid Manufacturing applications. During these studies two electroforming equipments were developed and manufactured, one for nickel and one for copper, which allowed the obtaining of electroformed shells for use in the rapid tooling applications: injection mold inserts with nickel shells by Monzón et al. (2006), copper EDM electrodes by Monzón et al. (2007), and recently, rotomoulding tools by Monzón et al. (2012).

The electroforming involves electrolytic deposition of a metal layer from the solution of an electrode of this metal, which acts as the anode of the system, over a cathode or model part to circulate a direct current. The whole system is immersed in an appropriate metal salt bath with the two electrodes. When current flows through the circuit metal ions in the solution are converted into atoms which are deposited on the cathode creating a metal layer. The main fields of application are:

- Manufacture of grid-like printing plates or cylinders.
- Production for radar waveguides.
- Micromanufacturing for medical, optical or mechanical components.
- Tools and molds.

The highlights of the electroforming capabilities are:

- Reproducibility of even the smallest detail of the model surface.
- Strict control over the physical and mechanical properties of the electroformed part by selecting the composition of the solution and process conditions.
- There is no size limitation on the electroformed parts from microns to meters.
- Geometric shapes can be produced that are impossible for any other method.
- Possible combinations of various metal properties and corrosion resistance, good thermal conductivity, high wear resistance, and others.

The main constraints of the process are the following: low deposition rate, non-uniformity in the thickness, difficulty controlling exterior surfaces, apply almost exclusively to products with thin walls and which have difficulty electroforming certain geometric details. Precisely, to improve thickness uniformity is the goal of the work presented here. Although the amount of metal deposited in a given time can be easily calculated by Faraday's laws, its distribution on the cathode is not uniform due to the influence of the current flow lines on the part geometry. To minimize this problem we have developed a tool to improve thickness uniformity of deposited material and reduce production times. That tool consists of a software application for analysis and simulation of the electroforming process, and a device for orientation of the workpiece model, which is programmed and controlled by the application. This product is called Elecform3D™.

2. Description of the problem

As mentioned above, the current distribution is determined largely through geometric factors such as the shape of the part and the relative location of it from the anode or other parts, as in the case of multiple and simultaneous electrodepositions. Moreover, at the corners, sharp angles, and generally in all sharp edges are a concentration of current lines as a result of charge accumulation leading to a local increase in thickness of the electroformed part, as seen in electroformed sample of Figure 1. Some of these effects are mitigated partially with suitable locations of the workpiece in the bath to improve relative position of the anode-cathode by Mouton (2005).

Some of the solutions proposed to solve the difficulty of uniformity in the electrodeposits are:

- Use of additives to improve the capability of the bath.
- Utilizing a pulsed current source with precise control over the output waveform and it can program pulsating cycles and reversing the polarity.

- Use of auxiliary anodes, barriers or sacrifice cathodes.
- Rotating the cathode, if the part geometry allows.
- Using computer simulation techniques for designing and configuring the electrolytic cell, in order to predict the characteristics of metal deposition.

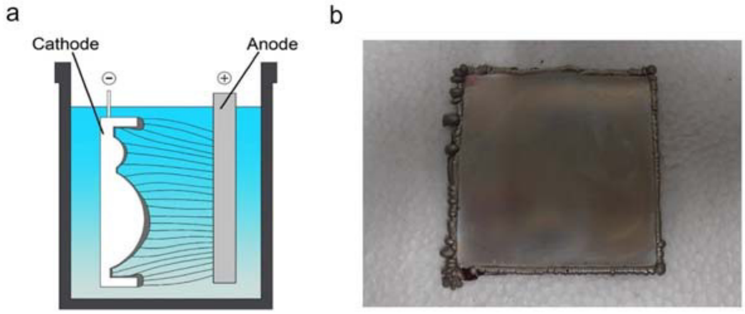

Fig. 1. (a) Scheme of electroforming process; (b) electroformed sample.

This work aims to improve the uniformity of electroformed shell thickness by developing an automatic device of cathode orientation (ADCO) that orientate the model and the electrical flow lines favoring the deposit in deep areas to the detriment of the most outstanding and favorable. With all that is sought after, averting or mitigating possible defects such as corner weakness, which is responsible for the failure of a lot of the tools manufactured by electroforming techniques. But to achieve this requires an analysis of the geometry of the part model and equipment employed in the electroforming process to determine the sequence of orientations and exposure time, that achieve the highest possible uniformity of thickness. For this, it has also developed a software application that provides an analysis and simulation module of the electroforming process in which an estimated thickness distribution after a sequence of cathode optimum positions, also previously determined. Has also been included a control module of ADCO allowing manual or automatic guidance during the process.

3. State of Art

Having developed computer simulation methods to characterize the design and configuration of an electrolytic cell in order to predict characteristics of metal deposits without having to resort to laboratory experimentation. With their use the cost and time involved in selecting the most suitable configuration for the deposition process is reduced.

In the market there are few analysis tools that simulate with varying degrees of accuracy the physical and chemical phenomena present in the electrodeposition process, thus allowing the evaluation of the quality of the deposits with different cell configurations and different operating conditions by Alkire et al. (1978). The fullest even allow the possibility of simulating the effect aids have on the final distribution of the workpiece thickness, the use of pulsed currents and multiple configurations of parts in the process by Van den Bossche et al. (2005)

However, all these products focus on the definition of the electrolytic cell configuration most appropriate for a given quality of deposits, allowing analyzing both 2D and 3D, which builds progressively with the addition to the model of calculating barriers and auxiliary anodes. It should be noted that many of these tools have been developed for applications to surface coating processes, where the wall thickness is much less than in the electroforming and therefore, its application is limited in this process. Other existing applications are oriented support tools in the experimental determination of chemical parameters for the characterization of electrolytic baths (polarization curves, conductivity, efficiency). Some have integrated design modules to define the geometry of the analysis model, while others have developed as integrated analysis modules in commercial CAD packages. Notably, all references found, work with a static configuration of the cell by Bullock (1990), which does not allow to model an automatic device of cathode orientation as it has been developed and presented here.

4. Automatic Device of Cathode Orientation

The basic purpose of this equipment is to move the model part for the electroforming process achieving a wide range of orientations regarding to the anode. The conceptual definition of the system and its modular design means it can fit any electroforming equipment with different characteristics. The requirements of accuracy and speed of the movements are not demanding for this application. The reliability and autonomy of equipment is an important aspect since it has to work continuously for several days. The common use of acid bath makes for a very aggressive working environment, hence it has been manufactured entirely of plastic materials resistant to these electrolyte solutions.

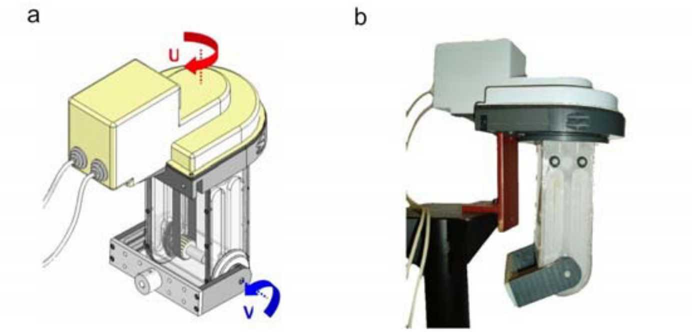

Fig. 2. (a) Scheme of ADCO; (b) Functional prototype of ADCO

This device comprises a mechanical and a control subsystem. The mechanical subsystem has two degrees of freedom, in the form of two rotary motions oriented U and V, whose axes are perpendicular. The workpiece clamping model is accomplished by a standard clamping system, versatile and simple, which is easily adapted to a variety of shapes and dimensions of the parts model. The control subsystem manages the movements and positions of both axes by a controller card and a simple software application that is the control module ELECFORM3D™ package. From this module are fed movement commands, so that it is not necessary to manipulate the device after the electroforming process is running. The control subsystem supports two modes: manual and automatic sequence. In the sequence mode, the control variables are the angles of two axes and the maintained time at each position. In Figure 2 you can see a scheme of this device, and the manufactured prototype unit has been adapted to an experimental electroforming equipment developed by this research group.

5. Analysis module

The development of simulation models that represent a certain degree of approximation is the result of the phenomena occurring inside an electrochemical cell and is not a simple task, because of the complex relationship between: electrochemical kinetics, hydrodynamic flow in the electrolyte and ion transport. Moreover, gas and heat generation in the control volume and in the electrode-electrolyte interface make the treatment and modeling of process a complex task.

The simulation of the distribution of current density on the cathode surface can be set to three degrees of approximation:

- Primary current density, which takes into account only electrical and geometric factors.
- Secondary current density, which also takes into account the above electrolytic specific factors taking place in the bath.
- Tertiary current density, which also includes material transportation factors due to the concentration and temperature gradients present in the electrolyte.

Experience in the field of metal electrodeposition allows despite those effects that certain conditions have been found to have little influence on the final result. With electrolyte baths where a proper relationship between cathodic polarization and the electrical conductance of current efficiency, among other factors, the thickness distribution on the cathode surface can be determined approximately, based only on geometric factors. This constitutes a substantial simplification of the problem and not covered kinetic effects and limitations by diffusion or concentration gradients, thus the influence of overpotential is negligible and only involve electric effects. Consequently, the current density and the thickness distribution on the cathode surface are determined by the relative position with respect to the anode cathode, ultimately, by the configuration of the cell. Based on this simplification, which corresponds to a model of primary current density as mentioned in the previous paragraph, we developed the first analysis module Elecform3D^{TM}.

By varying the relative positions of the cathode regarding the anode during the electrodeposition process there should be a sequence, or set of anode-cathode relative positions, wherein the thickness uniformity obtained is the "highest". In order to determine the sequence of movements or positions, the shell thickness at each of the positions of study must be evaluated, at least approximately, in order to select all the positions studied for which the thickness deviation about a mean value is minimized, or in other words maximized the degree of uniformity. Calculating the local thicknesses in each of the positions through analysis of the full model potential theory would be much more costly. This simplified model determines the thickness distribution in each of the scanning positions quickly at the expense of reduced precision in the thickness distribution calculated.

Based on the above, the proposed model takes as its starting thickness ideal theoretical thickness provided by Faraday's law, which is corrected by two coefficients. The first one is a function of anode-cathode distance, with it increasing thickness in the areas closest and decreasing in the farthest. The second coefficient is a function of the relative orientation of the cathode regarding the anode, that is, the angle formed between the anode surface and the cathode surface. It is an attempt to represent the reduction in current flow for which an area is affected due to distortion in the current lines. The determination of these coefficients is performed experimentally. Part for each orientation is defined by angles α and β, of the axes U and V respectively from ADCO, calculating the distances from each of the nodes of the cathode geometry to the anode surface and the deflection angle of the streamlines regarding ideally the flow direction defined by the normal vector associated with the anode surface, in each of the surfaces of the model part. It is thus possible to calculate the local thickness associated with each node of the model, and the average thickness of the deposit. To evaluate the uniformity of the distribution the standard deviation relative to the average is also calculated, obtaining the deviation coefficient, which measures the degree of dispersion of local values about the mean. If this procedure is repeated for a wide range of positions, you can determine a sequence of the same as to maximize the uniformity of deposit thickness.

6. Experimental assessment.

To evaluate the goodness of this simplified method an experimental test is proposed which produced a simple model consisting of a cube part with sides of 50 mm. Around electrodeposition of nickel in two different conditions was performed three orthogonal planes, figure 3. The first condition with the stationary model and with one plane facing the anode, and the second with changes in direction with the help of ADCO. These changes in orientation were that this device turned the part model every hour to address each of these three planes active at the anode. The other process conditions, current density, temperature and properties of the electrolytic bath were unchanged.

The initial objectives of this study were:

- Calculate the time required to reach a minimum thickness of around 500 microns at any point in the three planes.
- Evaluate the resulting thickness distribution on these surfaces.
- Determine the fitting curves for the coefficients of distance and orientation.

The minimum thickness is reached on central points of the faces, mainly due to the effect of edge growth. The figure 3 shows a representative distribution of the planes facing the anode, which corresponds to the XY plane of the test for changes in direction. In the XZ and YZ planes motionless test, the distribution is similar but asymmetric, minimum in the far side of the anode.

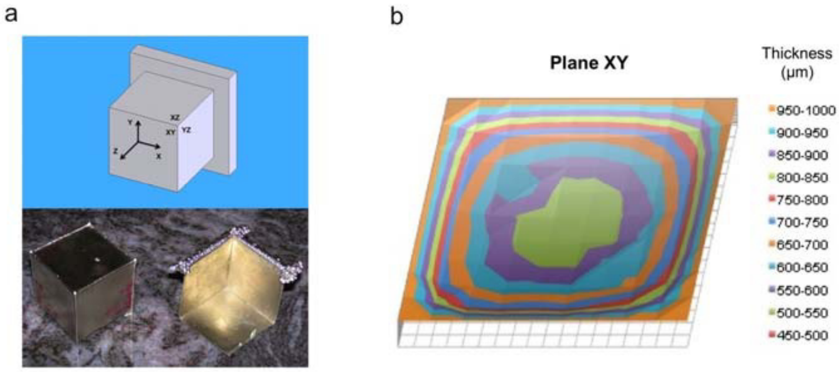

Fig. 3. (a) Model part and metallic shells; (b) Thickness distribution.

The measurement of these thicknesses was performed using a reverse engineering equipment overlapping surfaces of the part model before and after the test. The values obtained were validated with direct measurements using ultrasonic thickness precision gage, and a micrometer. A summary of the results obtained are shown in the table 1, which shows the minimum thickness of any of the planes, the average values in all three planes, and the time required for each test.

Table 1. Thickness results.

Test	Thickness (μm)				Time (hr)
	Min.	Av. XY	Av. XZ	Av. YZ	
Fixed	589	812	714	729	72
Moved	493	653	643	638	48

These results, while predictable, allowed the following conclusions:

- The orientation changes significantly improved thickness distribution, and decreased the effect of edge growth.
- There were significant time savings, which could be higher, as it could have applied a higher current density.
- The analysis of the geometric effects is very fast and allows for suitable positions sequences of the part model.
- The corrective coefficients did not allow predicting the growth of edge, and this is a very important distorting effect increasingly absorbing metal deposition by subtracting close surfaces.

For these reasons it was decided to continue this line of research, to develop an analytical model that considers the phenomena of electrochemical process being necessary, following the analysis method of secondary current density.

7. New analysis method.

The well known—potentials model of LaPlace enables deposited metal distribution prediction with high grade of precision, being experimentally validated. To be applicable, electrolyte must have uniform conductivity; a condition widely satisfied when the electrolyte is well mixed or when the ions involved in the reaction are responsible only for a small fraction of the ionic conductivity of the electrolyte. In this case thickness distribution could be studied through the following steps:

- Potentials distribution in bath determination for a certain potential difference applied between electrodes.
- Current density distribution starting from the potentials distribution.
- Thickness distribution on cathode applying Faraday´s Law

The problem domain (Ω) provided by the electrolyte is limited by the surfaces of the electrodes, anode (ΓA) and cathode (ΓC), in addition to the limits of the tank (ΓR). In Figure 4 is presented a schematic of the system.

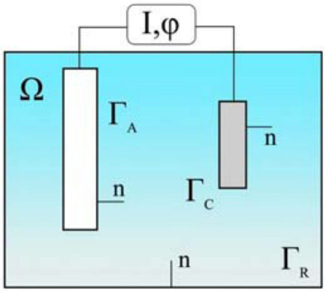

Fig. 4. Schematic of the analysis system.

The electric potential at each point of the electrolyte is determined from Laplace's equation Eq. 1, which describes the phenomenon of ion migration (movement of ions) due to the presence of an electric field.

$$-\nabla^2 u = 0 \qquad \text{in } \Omega \tag{1}$$

The system is completed with the boundary conditions at the edge from the tank and non-conductive surfaces Eq. 2, where the current density must be zero.

$$\sigma \frac{\partial u}{\partial n} = 0 \qquad \text{relates to } \Gamma R \tag{2}$$

On the active surfaces of the electrodes the current density is a function of the laws of polarization in the electrode-electrolyte interface. These relationships of intensity-potential difference are nonlinear, so that the whole problem is nonlinear Eq. 3 & 4.

$$\sigma \frac{\partial u}{\partial n} = f(u) \qquad \text{relates to } \Gamma C \tag{3}$$

$$\sigma \frac{\partial u}{\partial n} = g(u - \varphi) \qquad \text{relates to } \Gamma A \tag{4}$$

The current density vector is determined by the potential gradient in the electrolyte. This relationship is described through Ohm's law Eq. 5, and every point of the domain is shown by the expression Eq. 6.

$$\vec{J} = -\sigma \cdot \vec{\nabla} u \tag{5}$$

$$J_n = \vec{J} \cdot \vec{n} = -\sigma \frac{\partial u}{\partial n} \tag{6}$$

Consider the effects of polarization to determine the total current density J_{Tot}, and the cathodic current efficiency of θ (J_{Tot}). With all the deposited metal thickness δ is calculated by applying Faraday's law Eq. 7.

$$\delta = \frac{M}{nF\rho} \cdot \theta(J_{tot}) \cdot J_{tot} \cdot t \tag{7}$$

Laplace's equation, coupled with boundary conditions specified in the tank walls and on the surface of the electrodes, constitute a system of partial differential equations. Analytically the resolution of these problems is totally unworkable, at least for real geometries, so it is used for solving the employment of numerical methods. Since the resolution has been considered using the boundary element method (BEM), it is not necessary to discretize the entire domain of the problem. Simply divide the boundaries or contours of the same, so that surface elements are used rather than volume. As this discretization is achieved by significantly reducing the number of nodes processed, which makes them the most attractive method for solving problems where the domain is large and we are only interested in obtaining the solution of the problem on the surface or the contours of it by Dukovic (1990).

8. Conclusions.

In this research work we have created a new methodology for a little widespread and known process such as electroforming. No references were found in similar works that allow it to operate by a dynamic configuration of the electrolytic cell using an automatic device of cathode orientation.

Elecform3D^{TM} is potentially a step beyond for this process, which from the beginning has been conceived as a tool aimed at simple and practical industrial application of electroforming which could achieve high quality metal shells. It also allows to reduce manufacturing times, normally high in these electrodeposition processes, because with greater uniformity can use high values of current density which will enable functional thicknesses obtained in less time.

Therefore this product and electroforming are low cost technologies for metallic part production and can be combined with almost all additive manufacturing technologies, even 3D printers, with which can be got high precision and low cost model parts. This work enables new application fields for this process, although the proposal is mainly addressed to rapid manufacturing of tools.

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