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Experimental application of a laboratory equipment for micro-electroforming using models manufactured with additive technology

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Abstract: One of the manufacturing processes applications on a microscopic scale, consists in modifying parts or components´ surfaces to improve their properties. Unconventional machining processes are needed to generate complex geometries, high details reproduction, and excellent finished surfaces at that scale. Micro sinker electrical discharge manufacturing (μ-SEDM) process could be one good option. The electrode manufacturing is one of the main drawbacks. It supposes a big resources waste before starting to manufacture. In this way, working on a microscopic scale becomes a challenge to obtain different shapes and textures on functional surfaces. In this work, combined use of micro-electroforming and digital light processing (DLP) additive manufacturing is presented. These two additive techniques are completely different and unrelated in their applications, materials, and technological fundamentals. However, their combination is a low-cost option to obtain good results in the manufacture of μ-SEDM electrodes. Therefore, it was necessary to develop a micro-electroforming equipment to meet the challenge. Furthermore, device had to have the ability to adapt the process parameters to the needs of the parts. As a result of this experimental application, we got high-quality parts, which could have an industrial application.

Keywords: Micro-electroforming, Micro-manufacturing, Additive manufacturing, Micro-structured surfaces, Micro-sinker electro discharge machining.

1. Introduction

The integrated and advanced manufacturing research group of the University of Las Palmas de Gran Canaria (ULPGC) collaborates with the engineering materials and manufacturing technology group of the University of Cadiz (UCA) in a research project called Improving Functional Surface Performance through Texturization at Different Scales. Functional texturing consists of modifying the surface of the parts to improve their properties. Geometries with a certain pattern are applied, either under ingoing or outcoming surfaces. The objective is to generate geometric characteristics on the surface. This modifies their optical behavior (reflection, diffraction, and absorption), their tribological behavior (lubrication, friction, and wear) or their surface energy (capillarity, adhesion, and hydrophobia). Unconventional machining techniques such as electro discharge machining (EDM), electroforming and laser techniques are used to achieve details at different dimensional levels. One of these processes, sinker electro discharge machining (SEDM), requires a tool, which contains the structures that then generate textures on the surfaces of the workpieces.

The integrated and advanced manufacturing research group of ULPGC collaborates in this project with the task of generating the electrode, using manufacturing technologies that allow the reproduction of the intended details on a microscopic scale.

In addition, electroforming and digital light processing (DLP) additive manufacturing are two processes, which provide good results in this field. We decided to combine those manufacturing techniques. It was necessary to develop a laboratory equipment, which could adapt to the needs of both processes. The existence of outgoing and incoming geometries has been a challenge to achieve uniformity of thicknesses.

Both, additive and electroformed manufacturing, are processes, which have generated great attention in the field of micro-manufacturing, thanks to their ability to reproduce details. Those technologies mean an alternative, where conventional machining processes find some limitations. In other words, they offer possibilities that are unreachable for normal or common processes.

Additive manufacturing is the general term for technologies that create three-dimensional objects by successively adding material based on computer-aided design (CAD) modeling of a geometry [1]. In recent years, the technological innovation in additive manufacturing processes for polymeric materials has generated a substantial improvement in its functional and economic accessibility. Therefore, its use can be considered as a low-cost option. According to the manufacturing needs of the model, they can achieve excellent detail reproduction and dimensional control. There have been several studies, which have explored different technologies for the direct achievement of electrodes [2-5].

One of the oldest additive manufacturing techniques is tank photopolymerization (VAT photopolymerization). In this process, a liquid photopolymer located in a tank is selectively cured by the action of light [6]. To generate the design geometry with this selective curing, an ultraviolet (UV) light system is used. The UV light can be generated by a laser beam that runs through the area to be cured, or by a UV light source that is applied through a mask containing the geometry. This procedure is repeated for each of the layers, which make up the final piece. The ultraviolet light source distinguishes the two main variants of this process: stereolithography (SLA) and digital light processing (DLP). In DLP technology, different ways of projecting light can be used: a digital micro mirror device (DMD), which reflects and focuses ultraviolet (UV) light on the surfaces of the materials as a projector [7] or a liquid crystal display (LCD), which lights up with the image of the geometry to be reproduced [8]. In both modes, the photo reactive materials are polymerized layer by layer.

Electroforming is an electrochemical process that is defined as the production or reproduction of electrodeposition items on a chuck or mold that is subsequently separated from the tank [5]. The metal deposition seeks the generation of a shell that forms a piece itself because of the negative model [10]. Deposition takes place over time and depends on electrolytic bath conditions and process parameters. Shell thicknesses from 0.025 mm to 25 mm are considered good results of electroformed process [11]. Nickel, copper, and its alloys (Ni-Fe or Cu-P) are the most used materials as an anode. However, other metals can be deposited. The main limitations of the process come from a low deposition speed, almost exclusive application to thin-walled products, and the need to conduct electricity on the active surfaces of models [12]. To obtain closed three-dimensional geometries, it is necessary to work with lost models, which will become part of the piece along with the deposited layer.

Electroforming and its great capacity to reproduce three-dimensional geometries with dimensional accuracy has experienced renewed interest due to the existing demand for new working procedures to micro-manufacturing [13]. In certain applications it is presented as one of the few solutions for achieving good results, for example in the case of deep holes. In most other micro-machining methods, the difficulties of removing chips deep in the hole are a major drawback. This makes it difficult to work on geometries with a very high aspect ratio. In contrast, electroforming requires only a long core that can be easily adapted [14]. All things considered, it is a process which has great advantages in the field of microfabrication, such as dimensional accuracy, reproduction of surface details, as well as the manufacture of components with complex geometries and thin walls.

In recent years, a specialization of a process called micro-electroforming has emerged, aimed especially at the micro manufacture of components [15]. In this variant, special systems for electroforming equipment are used such as sources of pulsating energy with polarity inversion [16], or magnetic and/or ultrasonic agitation systems [17].

The integrated and Advanced Manufacturing research Group of the University of Las Palmas de Gran Canaria (ULPGC) has extensive previous experience in this field [18]. It has developed, among others, EDM electrodes for the manufacture of inserts for injection molds [19].

Using the EDM process, a complete machining has been carried out using electrodes with a copper layer thickness of 100 to 300 μm [20].

In this work, the first results of the experimental application of equipment for micro electroforming stage are presented. The target was to achieve the manufacture of a tool (electrode) for the μ-SEDM process. The paper presents a brief equipment description, its application in copper electrode manufacturing from resin models, and the results obtained.

2. Experimental Procedure

In this paper, the procedure to obtain copper shells with a functional pattern on their surface based on semi-spherical geometries on relief, is presented. These shells, with sufficient thickness, can be used later as an electrode for μSEDM processes to apply textures on the surface of a metal. That textures are based on semi-spherical cavities. The experimental process for obtaining the shells is divided into three phases: Additive manufacturing, Sputtering and micro-electroformed. It was necessary to develop a micro-electroforming equipment, based on the union of several components, to allow the combination of those processes.

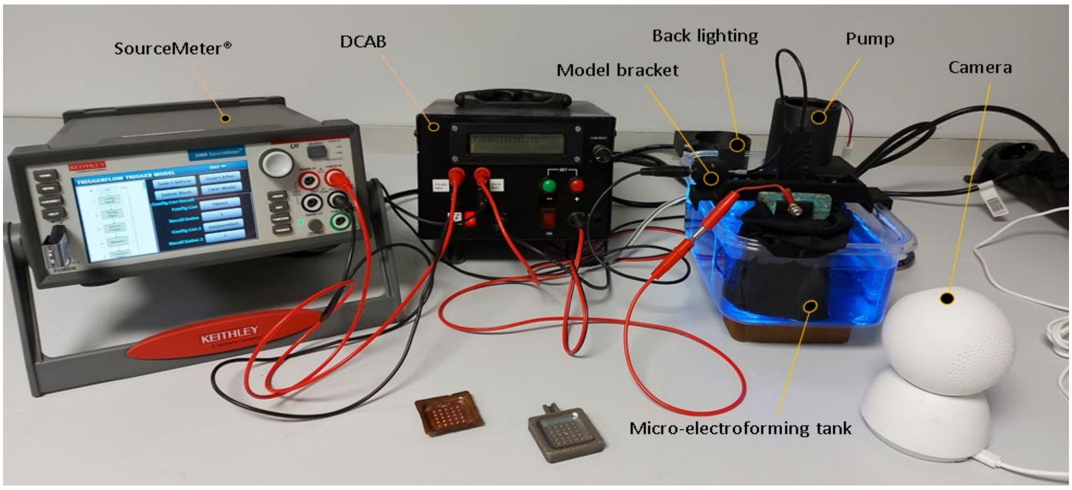


Figure 1. Micro-electroforming equipment at work conditions.

2.1. Description of the equipment

The equipment is composed of several elements that control the process parameters. Figure 1 shows the equipment in work conditions. These components are detailed below.

- Power Supply: An instrument, which combines the power source function and measurement functions (KEITHLEY 2460 SourceMeter®) has been used. It can make real-time measurements of all parameters in the Ohm Law (amperage, voltage, and resistance). At the same time, it can provide power with configurable output in voltage or amperage, according to the needs of the process. It is able to program electrical cycles and take and store readings of the electrical parameters of the process for further analysis. Figure 2(a) shows instrument data screen in work mode.
- Automatic electrolytic bath agitation control device (DCAB): This device of our own design and development, manages the electrolytic bath agitation system. It has a manual operation mode and a programmable automatic mode. In automatic mode the system compares the value of current intensity, which circulates through the circuit and the intensity of setpoint current. Based on this comparison, it adjusts the power value of the submerged pump to increase or decrease the recirculation flow of the electrolytic bath. Besides, an Arduino nanus with open programming code has been used to control the system.

- Model clamping system: This component is responsible for supporting the functional model. It has three-axis movement to allow the adjustment of the distance between anode and cathode, and its orientation by means of X-axis and Z-axis offsets.
- Agitation system: It consists of a submersible radial flow centrifugal pump with a maximum drive flow rate of 2.88 l/min. It has a collector for the distribution of the flow with 5 outlet points. According to research needs, this collector is detachable, allowing experiments to be conducted under laminar flow or turbulent flow conditions. Furthermore, it has a backlight system with Led light that allows to visualize the progress of the deposition.
- 360° video surveillance system: It allows tracking of electrodeposition in real time by a smartphone application. It has continuous recording mode and the possibility to obtain images at any moment of the process. Figure 2(b) shows an example. This system has been very useful for further analysis of finished parts.

(a) (b)

Figure 2. (a) SourceMeter® data screen. **(b)** Surveillance and backlighting system view.

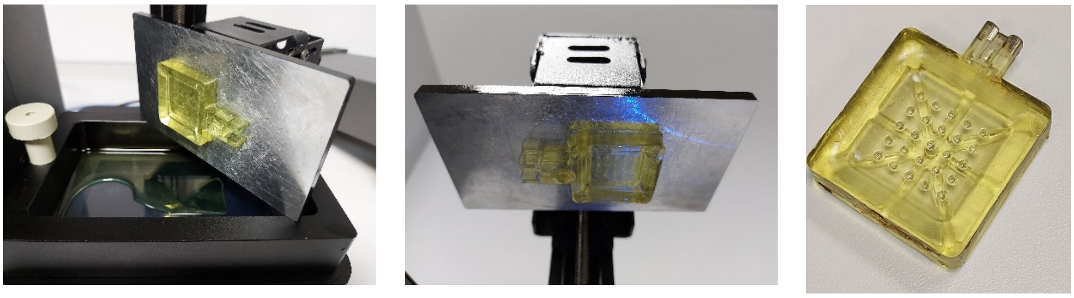


Figure 3. Functional model manufacturing.

2.2. Manufacture of the functional model

Additive manufacturing technology by digital light processing (LCD/DLP) has been used for the manufacture of the model. A machine with value less than 500€ has been used. A very low cost when compared to evaluations made by some authors for direct manufacturing methods [3]. Its accessibility and low cost were raised as a very interesting option for industrial applications. In these early phases, it was decided to work with a square model with the external dimensions of 38×38 mm. It has a functional surface with 25 semi-spherical cavities of 2 mm in diameter, rounding of radius 0.5 mm and pitch 4 mm between centers. Several resins were tested in opaque and transparent finishes. Finally, transparent ones were selected, because the use of backlighting makes it possible to visualize the uncoated areas during electrodeposition process. A deposition of 247 layers of 30 µm thickness was used to manufacture the pieces. An exposure time of 4s was used. The most relevant difficulties of the process were: the trapping of resin in the finest details during the curing process due to the high density of the polymeric material; the limitation of details in the reproduction due to the resolution of the LCD screen of 47×47 µm; the pixelated; the differential deformations that generate shrinkage distortions. In this case, it was necessary to increase the thickness of the model and place ribs on the back to provide rigidity to the part. Figure 3 shows the result.

2.3. Metallizing

The electric current must circulate through the cathode to perform the micro-electroforming process. Therefore, it has to be conductive. Once the functional model on polymeric material is obtained, the next phase is to generate electric conductivity on the active surfaces. A gold-palladium spraying process (sputtering) with luminescent discharge in the presence of argon was used to fulfill the surface treatment. Figure 4(a) shows the discharge camera of the SC7620 Mini Sputter Coater, where the process was performed. Parameters that were recommended by the manufacturer consist in a plasma current of 18 mA at a voltage of 1 kV for 120 seconds, which provides a theoretical layer of 367 Å. Three depositions were made with an equivalent thickness of approximately 1 nanometer to ensure the correct coating of all functional geometry. Figure 4(c) shows that the coating reproduces all surface details in the model part. There are no alterations of the geometry on the work scale required for this application. The metallizing was so complete that it generated an unwanted coating effect on the perpendicular faces of the model. This forced a subsequent masking process to prevent uncontrolled growths on those also conductive surfaces, figure 4(b). To verify the result, visual inspections were performed with a Mitutoyo TM-510 measuring microscope, figure 4(c).

(a) (b) (c)

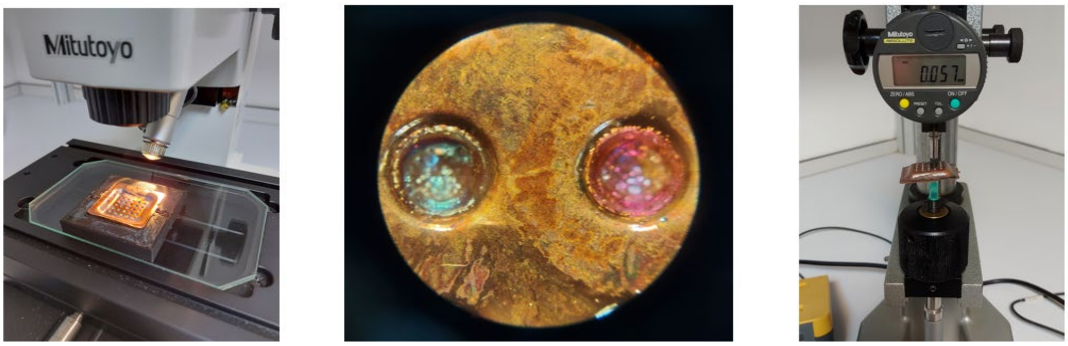
Figure 4. (a) Discharge chamber. **(b)** Metalized model with lateral protection. **(c)** Microscopic view of the result.

2.4. Micro-electroforming

The test procedure was designed to run in 4 phases under controlled laboratory ambient conditions with a temperature of 21°C and a relative humidity below 70%. Work sequences were performed in different time intervals: by setting the current intensity values in two of the stages and the voltage values in the other two. The control of the operational parameters of the process was executed by the programmable power supply, and the control of the agitation of the electrolytic bath by the DCAB*,* so allowed the automatic modification of the fluid recirculation flow in the electrolytic tank. Tests were carried out under laminar flow conditions. A monolithic piece of Cu-P with dimensions of 100×50×10 mm were used as an anode. The electrolytic bath was composed of a copper sulfate acid solution for applications of soft finishes and high gloss. The distance between anode and cathode was set 100 mm with a facing orientation (0°).

2.5. Inspection and measurement

In this phase, the finished part was reviewed to see if it met the established requirements. No other manufacturing process, whether conventional or unconventional, could achieve outgoing hemispherical geometries without altering the surface. A visual inspection was performed using a measuring microscope (MitutoyoTM-510) to verify the surface quality, figure 5(a). Shape defects or lack of deposition were sought. Figure5(b) shows surface quality. Then, an inspection was carried out from a functional point of view. It was verified that the thickness dimensions of the part had reached the requested values and they had placed uniformly. The equipment and facilities of the Metrology and Calibration Service (SMC) of the University of Las Palmas de Gran Canaria were used. Measurements on the surfaces of the parts and at the bottoms of the semi-spherical cavities were made with a mechanical comparator Mitutoyo ID-C112B, figure 5(c). The equipment had a calibration certificate (Nº862) (Nº616) issued by the SMC of the University of Las Palmas de Gran Canaria.

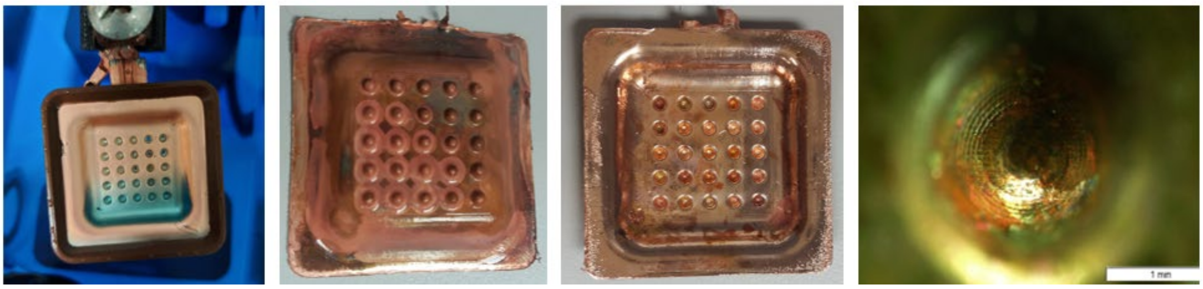


(a) (b) (c)

Figure 5. (a) Microscope inspection. **(b)** Surface, microscope view. **(c)** Measure process.

3. Result and discussion

After a series of initial experiments, where the process parameters were adjusted and the performance of the equipment was optimized, a test procedure was determined. This procedure was used for the achievement of valid parts for further use in the electrical discharge machining (EDM) process. It was possible to improve the thickness distribution throughout all geometry, even in ingoing surfaces, under repetitive conditions. Figure 6(a) shows high quality reproduction of model´s geometry. Figures 6(b) and 6(c) show that all the bottoms of the semi-spherical cavities with micrometric scale were completed. Microscope inspection shows how deposition was able to reflect the details of the functional model. In figure 6(d) the formation of rings can be observed in detail. Those rings were the faithful reproduction of the layered deposition during the digital light processing (LCD/DLP) process.

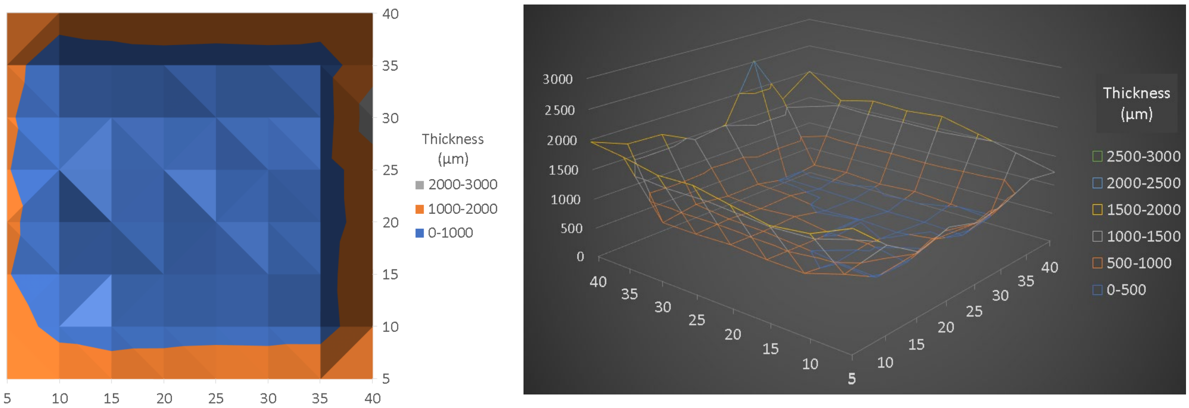


(a) (b) (c) (d)

Figure 6. (a) Micro-electroforming result. **(b)** Functional surface. **(c)** Non-functional surface. **(d)** Rings details, microscope view (x5).

First process step, with low and constant current intensities, was shown to be decisive in controlling the detail generation stage. Geometric details, which were not defined in this stage, did not exceed the growth stage, and became definitive surface defects.

Measurements on one of the parts selected for use in the EDM process, indicated average thickness on the functional surface area of 518 µm and a minimum value of 383 µm. The bottoms of the semi-spherical cavities reached an average value of 406 µm and a minimum value of 328 µm. Figure 7(a) graphically shows, in blue, the uniformity of thickness distribution on functional zone. The greater thickness on the border, in orange, is an expected result. In electroforming, outgoing geometries are easier for deposition. Figure 7(b) shows how three-dimensional thickness distribution matches part geometry. It shows the influence of the incoming and outcoming on deposition areas.



(a) (b)

Figure 7. (a) Thickness distribution. **(b)** 3D thickness map.

Exhaustive control of the parameters, which were governing the micro-electroforming process, were decisive to achieve good results in repetitive conditions. Feedback from SourceMeter® data helped to understand the electrical behavior of the deposition process. Using this data as a reference for subsequent tests, allowed the optimization of the process. The ability to schedule duty cycles brought reliability to experiments.

4. Conclusions

Combined use of additive manufacturing, sputtering and micro-electroformed processes demonstrated great potential in shaping functional surfaces for the use in micro sinker electrical discharge machining (µ-SEDM). Additive manufacturing by digital light processing (LCD/DLP) obtains high quality functional models in the reproduction of details with low-cost technology. The metallizing process is reliable and technologically compatible to achieve conductivity on active surfaces. The sputtering cloud ensures the correct coating of the entire surface. The developed equipment for micro-electroforming operations shows to be effective in generating viable copper shells. Its versatility and ability to adapt to the needs of the micrometric scale deposition process is valid. Agitation of electrolytic bath under laminar flow conditions, especially in the early stages of deposition, demonstrates a significant improvement in results allowing greater uniformity in the deposited surface. In this way, one of the main limitations of the manufacture of these electrodes by other machining processes, outgoing hemispherical geometries, can be overcome. After the analysis of the geometric characterization of the selected test parts, we conclude that we have reached optimal thicknesses, exceeding the reference values (100-300µm) tested by some authors for EDM work.

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