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# Design and manufacture of structured surfaces by electroforming

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**Abstract**

Functional surface texturizing is increasingly demanded by multiple industrial sectors because it allows to achieve properties that significantly improve the functional characteristics of many products. The surfaces structured with geometric details at micrometric scale are allowing a selective modification of their properties. The electroforming process is acquiring a major role in the manufacture of microstructures, due to its great capacity for reproduction of details. The University of Las Palmas de Gran Canaria has extensive experience in rapid tooling through the electroforming process and is collaborating with the University of Cádiz in the ELECTROTEX project to Study of the Tribological Behaviour of Textured Surfaces by SEDM. This collaboration consists of the development of a SEDM electrode with a structured surface for the machining of test specimens for tribological tests.


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## 1. Introduction

Surface engineering is currently playing a key role in the development of many industrial applications, among other things, a geometric selective surface modification of a product improves the functional properties. The functional

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texturing can be achieved by applying a given geometric pattern, micrometer scale and both low relief and over-relief extended to the surface on which you want to alter their behavior, resulting in so-called structured surfaces. Properties such as adhesion, friction coefficients between the surfaces and behavior in contact with different types of fluids, are clear examples of their applications. Furthermore, they have the advantage that they are easily replicated using traditional mass production processes in polymeric materials such as injection molding, hot embossing, and lithographic printing. Actual uses of these micro-structured surfaces are already in the fields of microelectronics, information and communication technologies, tribology, biomedicine, automotive, aerospace, optics, energy, mechanics, thermodynamics, hydrodynamics and coatings. In this context, surface engineering presents a situation of intense expansion continually extending their fields of application.

This work is part of the ELECTROTEX project Study of the Tribological Behaviour of Textured Surfaces by Seed Electro-Discharge Machining (SEDM), which is developing the Engineering & Technology of Materials & Manufacturing research group (INTEMAFA) of the University of Cádiz (UCA) and which is collaborating at the University of Las Palmas de Gran Canaria (ULPGC) through Integrated & Advanced Manufacturing research group. The work package in this project is the development of an SEDM electrode, for use in functional textured surfaces with tribological applications, using the electroforming process. The basic objective of this work is to perform the design of this tool and expose the manufacturing stages required by the electroforming process.

## 2. Background

In this section a brief description of the state of art and previous experiences related to the electroforming process and the structured surfaces will be made.

### *2.1. Electroforming*

Electroforming is defined as the production or reproduction of articles by electrodeposition upon a mandrel or mold that is subsequently separated from the deposit, according to ASTM B832-93 "Standard Guide for Electroforming with Nickel and Copper". This electrolytic process has been known for a long time, but has become especially interesting in recent decades. Its main fields of application are the manufacture of grid products such as plates or printing cylinders, to radar waveguides, micro components for medical, optical or mechanical applications and tools for other manufacturing processes [1]. The most important capabilities of electroforming are the ability to reproduce even the smallest details of a surface and very accurately, and strict control over the physical and mechanical properties of the electroformed part by selecting the composition of the electrolytic baths and process parameters.

Electroforming involves the electrolytic deposition of a metal layer from the dissolution of an electrode of this metal which is the anode of the system, on an electrode model that will constitute the cathode of the system. Continuous current is applied between the anode (+) and the cathode (-) with the entire system immersed in an appropriate solution or bath of metal salts with the two submerged electrodes. When the current flows through the circuit, the metal ions present in the solution are converted into atoms that are deposited on the conducting surfaces of the cathode, creating a more or less uniform metal layer or shell [2]. Therefore, electroforming can be considered as an ionic additive manufacturing process where the material is deposited in layers which do not have to be flat.

The main limitations of this process are a low deposition rate, almost exclusive application to thin-walled products, and the need for electrically conductive models on their active surfaces. None of them significantly affects the manufacture of micro-shells with high dimensional accuracy, precise reproduction of surface details and fabrication of components of complex and thin-walled geometries. Therefore, the electroforming process has great advantages in the field of micro-manufacturing.

In fact, a variant of the process specifically directed to the microfabrication of components called micro-electroforming has emerged in recent years [3,4]. In this specific line, very good results have been obtained in obtaining metallic microstructures with electrolytes of nickel sulfamate, which allows deposits with relatively high deposition rates and low internal stresses [5,6]. In this variant special systems are used for electroforming equipment, such as pulsating energy sources with polarity inversion, magnetic and/or ultrasonic agitation systems, relative movements and orientation of the electrodes, in addition to the application of vacuum conditions during the process [7–11]. These systems allow a very specific electrodeposition adapted to the part geometry, modifying the crystalline process, the structure and with it the final texture obtained and the imitation quality of the model part. When requirements require stringent tolerances, light geometries and component miniaturization, electroforming is a serious competitor and in some cases the only manufacturing process possible or economically viable [2].

The Integrated & Advanced Manufacturing research group of the ULPGC, has extensive experience in the use of electroforming process. Among other applications, a methodology has been proposed for the development of EDM electrodes through this electrolytic process [12]. In Fig. 1, a copper electrode obtained by electroforming is presented next to the machined cavity. You can also see the required model piece, manufactured using an Additive Manufacturing (AM) technology, with the texture for aesthetic purposes applied on its surface. It can be seen how that texture was copied down to the smallest detail on the electrode by the electroforming process and subsequently transferred to the cavity by the EDM process.

### *2.2. Structured Surfaces*

Engineering surfaces are those whose geometry is intentionally altered to achieve properties that allow variation in their functional behavior. It establishes a clear difference with the surfaces obtained in any piece, when applying the manufacturing process that has given its shape, in which there is no direct intention to influence its surface properties. The geometrical analysis of the latter surfaces is performed using assessment techniques surface texture while evaluating specific geometric micro-scale features and repetitive, as normally occurs in surfaces engineering, is beyond the scope of these techniques. In this case, surface micro-topography techniques are used to analyze the geometric properties of real surfaces, and within this domain engineering surfaces are classified into two large groups: stochastic or random and structured [13,14].

- Structured surfaces are those with well-defined geometric characteristics, normally micrometric in scale, which are distributed on the surface with a well-defined geometric pattern. While stochastics have either random geometric characteristics or their distribution on the surface is considered to be of a random character. These stochastic surfaces can be classified into uniform or isotropic when there is uniformity in the arrangement of the geometric characteristics, and in directional or anisotropic when there are well differentiated directions in which these characteristics are arranged. Meanwhile, structured surfaces are classified into four major groups[15]: Tessellated or mosaic type, where the surface topography is dominated by a geometric pattern of finite dimensions that covers the entire surface without overlaps or voids.
- Linear, with a surface topography marked by linear characteristics that are repeated in a direction perpendicular to them in the whole of the surface.
- Rotational, whose surface topography is defined by elements with rotation symmetry and are repeated when rotating a certain angle.
- Multi-pattern, where its surface topography is formed by several different geometric patterns or the surface cannot be included in any of the other types.

We have found multiple applications in the manufacture of micro-structured surfaces by electroforming in intermediate process tools of large production chains, contributing significantly to the mass production of products [16,17]. Some references have also been found in similar applications in the rapid manufacture of tools for processes such as electrochemical machining or EDM [8,18].

## 3. Methodology

The ELECTROTEX project has as basic objective the evaluation of the tribological behavior of texturized surfaces generated by specific geometric patterns, that allow to improve the functional performance of those surfaces. There are many experiences that have shown that in this type of contact surfaces the friction is reduced, the temperatures in service are reduced and the useful life of the components increases. This is due to the fact that the areas in contact are diminished and that in the geometric details the lubricant and the abrasive particles which have been detached from the contact zones are retained, thus avoiding the abrasive effect thereof.

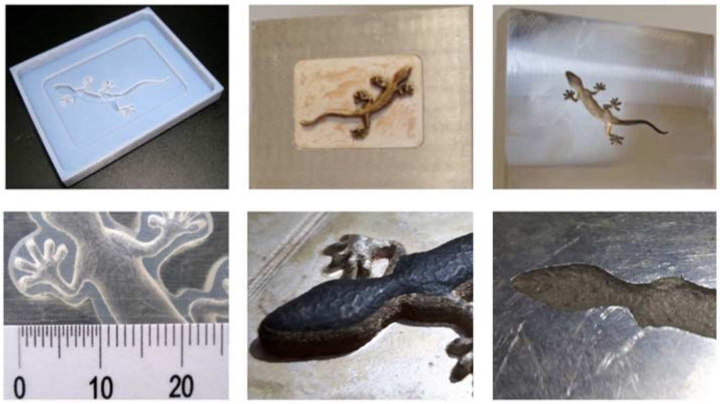


Fig 1. Details of texturing in AM model part, copper SEDM tool and steel cavity.

In this project it has been proposed initially to use structured surfaces of tessellated type to generate the surface texturing, using as basic geometric elements hollows in tetrahedral and semi-spherical form. This texturing is intended to apply to a functional surface of some test specimens for tribological characterization tests by the SEDM process. In Fig. 2, a preliminary design of the required electrodes with the dimensions and textured surfaces that are required in relief can be observed, which after the EDM operation will generate the micro-holes in the surfaces of the specimens. Both geometric details have a characteristic dimension of 1 mm, side or diameter, a depth of 0.5 mm and extended on a flat surface of 50x50 mm in a square matrix of passage 1 mm. The manufacture of these electrodes presents certain peculiarities since, for example, the tetrahedral forms would be relatively simple and quick to generate by means of milling or WEDM, whereas the semi-spherical protuberances, with those geometric characteristics, would be very difficult to manufacture with those processes, but relatively simple to manufacture them by the electroforming process.

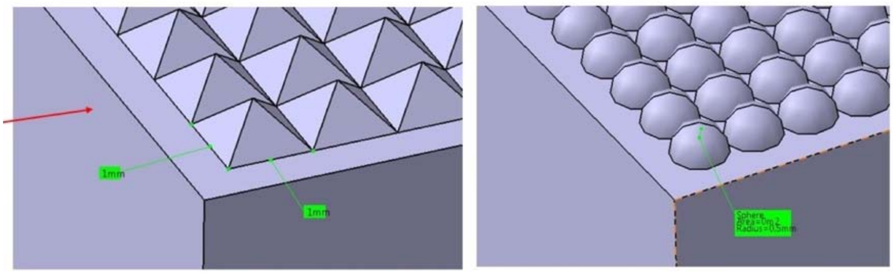


Fig. 2. Preliminary design of proposed electrodes and structured surfaces.

For this reason, according to the capabilities of the equipment available and the experience of the Integrated & Advanced Manufacturing research group in the development of rapid tooling, it has been decided that its participation in this project focuses on the manufacture of the electrode with the semispherical geometric pattern. This tool will be manufactured by the process of copper electroforming, since this type of shells have shown feasibility and suitability for use in tools for finishing operations, as is required in this texturing application.

As mentioned above, for the application of this process a model part is required on which the electrodeposition will be carried out, on the active surfaces that have to be conductive of the electricity. The material of the model part may not be electrically conductive, and in this case a surface coating will be required to achieve that electrical conductivity. Given the dimensional characteristics of the structured surface, and in order to achieve a minimal geometrical alteration of the same, it has been decided that the model part is made of electrically conductive material. The initial intention was that the material used was the same aluminum alloy as the UNS A97050 tribological test specimens, and it shall be necessary to shield or cover with a protective film all those non-functional surfaces of the model part to avoid metallic deposition on them.

Before closing the final design of the electrode, it has been decided to carry out preliminary electroforming tests on a smaller model part with the same geometric pattern of the structured surface. This piece has been manufactured in 6063 T6 aluminum alloy by milling and micro-drilling in a high-speed machining center MAZAK VTC 300 C II. The micro-drilling tool used, SS White BULK 100 FG CARBIDE 2P with 1 mm head diameter and 4 flutes, and geometry and dimensions of model part can be seen in Fig. 3.

Once this model piece has been machined, a simple geometric characterization has been made, in the Metrology Dimensional lab of the Mechanical Engineering Department of the ULPGC. This metrological information will allow a comparison with that obtained for the copper shell generated from it, thus analyzing the replication level of the texturing. A NIKON V-12A profile projector has first been used to get an overview of the textured surface. An appreciable geometrical distortion has been observed which is considered due to a possible deformation of the micro-tool, causing a clear misalignment of the semispherical holes in both main directions. It is also observed the presence of micro-burrs that condition the geometric characterization and could distort the actual surface of the electroformed shell, Fig. 4.

An OLIMPUS BX51+BXRLA2 optical microscope, provided with UIS optical system and Olympus DP72 digital camera, has also been used to make a more detailed and accurate measurement. The calibration of this equipment carried out to references of the CEM (Centro Español de Metrología) and the global uncertainty of the measurement process it was estimated to be 0.57 μm. Objectives 2x and 5x have been used to be able to have a field of observation suitable for measurement between several geometric elements. With the 2x objective one can observe approximately a quarter of the total textured surface, the positioning of a large number of micro holes can be measured to determine the deviation of the alignment with respect to the end elements and the two main axes. This measurement was repeated in the four quadrants to sweep the entire textured surface. In Fig. 5, one of these images can be observed with the corresponding measurements. With the objective 5x a measurement of the diameters and distances between centers of the micro-drills was carried out in a smaller field of measurement and in 5 zones representative of the textured surface: in the center of the same and in the limits of the surface in the directions of the main axes of the piece. Fig. 5 shows an image with the measurements and a clearer view of the micro-burrs generated in the machining.

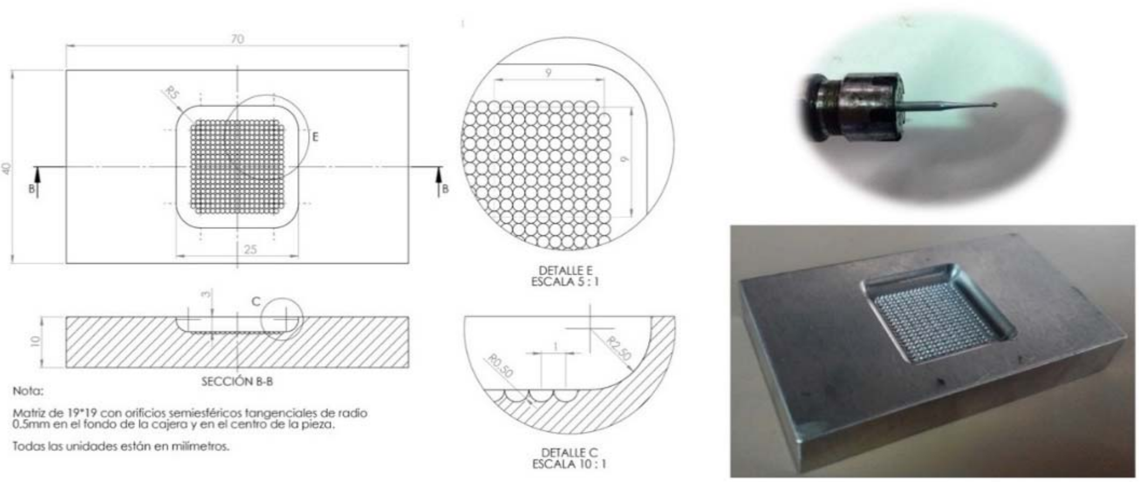


Fig. 3. Model part and micro-drilling tool for electroforming test.

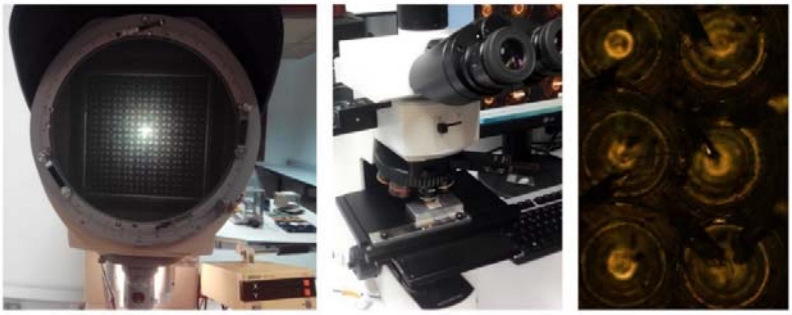

Fig. 4. Measurement equipment used in geometric characterization and micro burrs.

Once the geometric characterization of the part has been carried out, the model part is prepared for use in the copper electroforming process. A clamping system designed for test pieces of these dimensions is used, which in turn allows the shielding almost all non-active surfaces. However, it has been found convenient to apply an easily removed protective varnish on such surfaces to prevent metallic deposition in undesired areas. After the electrical connection of the model part, the assembly is inserted into a small laboratory test cell with a copper sulphate bath. In the power supply used for the test, the current is adjusted to achieve a current density of approximately 1 A/dm2, in order to achieve the best reproduction quality of the surface of the model part. After 48 hours of deposition proceed the separation of the obtained copper shell. In Fig. 6, the laboratory equipment used for electroforming, the copper shell obtained next to the model part, a side profile view of the shell, and an image of the microscope with the measurement of several spherical protrusions can be seen.

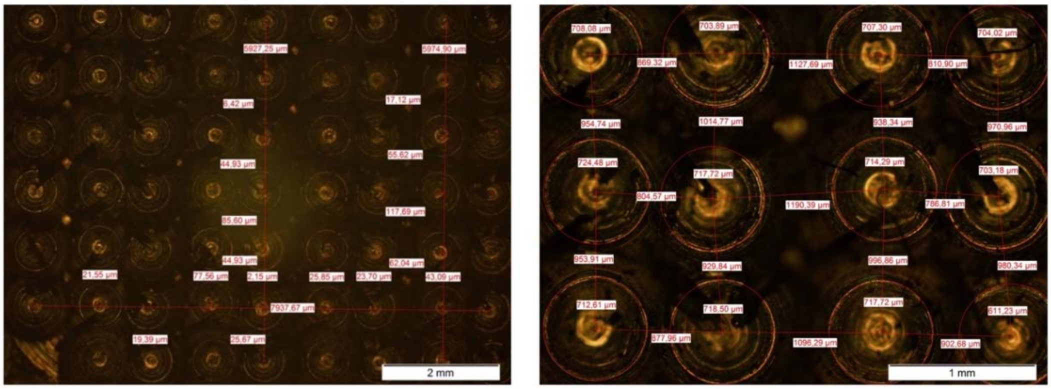


Fig. 5. Microscope images with measurements with 2x and 5x lenses.


Fig. 6. Electroforming equipment, copper shell obtained, side profile view and microscope image with measurements.

## 4. Results

The results obtained in the machining of the test part suggest that initial design modifications should be made to the structured surface. The high density of the micro-holes with tangent contours generate deformations in previously machined holes. Measurements show a maximum misalignment of 211 microns, with more than 90% of micro-holes having a misalignment of less than 100 microns. This suggests using a tool of greater rigidity for this machining in order to achieve a more even distribution of the structured surface.

Moreover, from the functional point of view a sufficient contact area is required to avoid high stresses between the surfaces in contact that alter the texture. The approximate total area of this textured surface is 2025 mm2 (45x45 mm), the contact area of 440 mm2 being only 21.7%. For this reason, it has been decided to increase the spherical pattern of the drill using a tool of 2.5 mm in diameter, which deepens 0.5 mm on the surface and generates a circular footprint of 2 mm in diameter. This spherical element is repeated in a square matrix of 15 x 15, with a pitch of 3 mm. With this new design the area of contact becomes 1313 mm2, which represents 64.8% of the total area and three times greater than in the initial design. If the maximum volume of lubricant and particle retention in the voids is compared, it passes 527 mm3 in the initial design to 191 mm3 in the modified design, a reduction of 64.5%. This is mainly due to the drastic reduction of number of micro holes from 2025 to 225, 11.1% of those in the initial design.

After the electroforming test, and as can be seen in Fig. 6, a complete definition of the semi-spherical surface has not been achieved, due to the high density of micro-holes tangent to each other, deformations during machining and micro-burrs. It has also been observed that due to these defects in the structured surface of the part model has produced a greater mechanical anchoring of the copper shell over it, causing copper remains on the model piece to stay. After an analysis of the surface condition of the model part, it has been observed that some areas have resulted in a very significant degradation, produced by the specific characteristics of the copper sulphate electrolytic bath used. This degradation of the model part has contaminated this bath, which together with the lack of agitation, has produced a stratification in the concentration of copper. All this has generated in the copper shell a burned area that clearly affects the quality of the obtained structured surface.

A change in the material proposed for the model part is required to make it chemically stable inside the bath. The most logical option is to use a titanium alloy, because of this material are the anodic baskets that are used in the electroforming equipment. Other possible option is to use a bronze alloy, which is also a material frequently used in the manufacture of parts models permanent ducts, but it is necessary to do a test to confirm its use.

In the design of the electrode roundings have been introduced in the edges of the textured surface to avoid edge effects that cause a distribution of non-homogeneous thicknesses in the electroforming process, and also to facilitate the manufacture of the necessary model part. Other geometric elements are included in the outer contour of the model so that it can be integrated into a specific tool that can incorporate a standard Hirschmann type electrode holder. This tool allows precise positioning of the copper shell, adequate fastening to the EDM machine and facilitate its geometric referencing prior to the machining operation. This tool was developed by the research group in Integrated and Advanced Manufacturing within the framework of a doctoral thesis entitled Definición del proceso y estudio del comportamiento de los electrodos para EDM fabricados mediante técnicas de Prototipado Rápido (RP) y procedimientos de Electroconformado (EF) [19]. In Fig. 7, the designed electrode and the model part required for its manufacture can be observed and the electrode holder where it will be used.

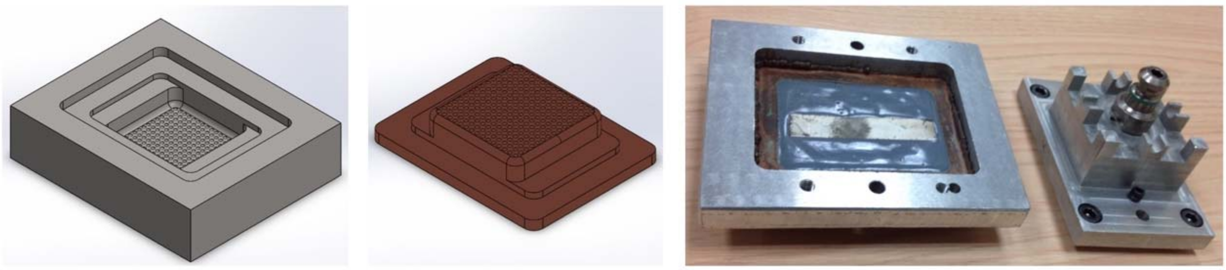

Fig. 7. Electrode final design, model part and electrode holder.

## 5. Conclusions

The electroforming process has shown great potential for the production of textured surfaces thanks to its great detail reproduction capability. Its main limitation is the need to have a model piece that must have the texture to be achieved in the final piece. When micrometric scale features are required on the surface, manufacturing processes capable of generating such model parts, which in addition are to be conductive of electricity on their active surfaces, are required.

After the analysis of the measurements obtained in the geometric characterization of the test part, it is concluded that a micro-drilling tool with a higher rigidity and a high number of flutes is required, in combination with an adjustment of the cutting parameters of high-speed machining, to try to achieve a more precise textured surface, without deformation and clean of burrs.

A new design for the structured surface has been proposed which allows better operating conditions for tribological applications, and which is better suited to its reproduction by the electroforming process.

Although aluminum alloys are frequently used in the manufacture of conductive and disposable model parts, it has been confirmed the need to change the material of model part, to incorporate a cathodic agitation system in the process to improve the bath renovation in the deposition zones and to achieve a higher quality of reproduction in the shell.

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