Metrological assessment of microtextured EDM electrodes generated by additive manufacturing and electroforming

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Abstract. Surface engineering makes use of functional and aesthetic textures to meet different needs in the development of new products, with high-value enriched features. At present, the use of additive manufacturing is bringing many advantages in its integration into advanced hybrid manufacturing processes. The direct application of textures on 3D models is a viable, fast and sustainable solution in many of these technologies by reducing the consumption of resources in materials and energy, of the additional processes that have been commonly applied in these applications. One of the processes that allows texturization of materials with great hardness is sinker electro discharge machining. This process, although slow, allows to obtain textures in small dimensions with very high precision, difficult to achieve by conventional processes. However, one of the aspects that make it a slow and expensive process is the manufacture of electrodes, especially those with complex geometries. Therefore, work is being done to solve this aspect, combining the additive technology of stereolithography by mask (MSLA) and the electroforming process to generate micro-textured copper electrodes with some structured and bioinspired textures. The model parts are generated with the textures in MSLA, which are then metallized on the functional surfaces before being introduced into the electrolytic bath to generate the electroforms with the appropriate thickness. This work presents the results of the metrological assessment from the CAD modeling to the electroeroded part, including the generated model part and the electrode made from it. This work is being developed in the Integrated and Advanced Manufacturing research group of the University of Las Palmas de Gran Canaria and in collaboration with the Engineering and Materials and Manufacturing Technology research group of the University of Cadiz.

Introduction

Over the last century, advances in Surface Engineering have originated as a result of widespread knowledge about how contact mechanisms are influenced by surfaces. All the surfaces present in our environment have texture and structure, some of which have been expressly designed by engineering [1], or are characteristic of the nature of the materials or processes of the transformation processes to which they have been subjected. Likewise, on these take place the most important physical phenomena, such as the exchange of energy and the transmission of signals. It is for this reason that the role played by the understanding of the phenomena present in the surfaces, mainly at micro and nanometric scale, has allowed developing numerous advances in fields such as electronics, biology, biomimetics, information technology, etc. Moreover, technological progress in the field of micro-manufacturing allows the functional exploitation of certain phenomena by reducing dimensions.

The surface of a solid, or more precisely a solid-gas or solid-liquid interface, has a complex structure and properties, dependent on the method of surface generation, the nature of solids and the interaction between the environment and the surface. For their interaction, the surface properties of a solid are crucial, because such properties affect the real contact area, which for example are very important in friction mechanisms, wear and lubrication. Along with tribological functions, surface properties are important in other applications, such as optical, electrical and thermal performance, or appearance [2].

One of the greatest technological challenges of modern engineering is to try to reduce the negative effects caused by the phenomenon of wear. This is a problem that is relevant to the life of metal parts [3]. That is why numerous investigations have been carried out with the aim of finding ways to improve friction and wear resistance of this type of surfaces, discovering that by developing specific surface topographies functional applications could be obtained [1, 4, 5].

However, the different surfaces of solids, without taking into account the method of elaboration, contain irregularities or deviations on the theoretical geometric form prescribed, known as surface finish [6, 7]. None of the machining methods, no matter how precise, can produce a completely flat surface in conventional materials. Even those surfaces with more demanding finishes contain irregularities whose heights exceed the interatomic distances. In addition, occasionally, there will be a fatty or oily film derived from the environment. These films are found on both metallic and non-metallic surfaces and affect both friction and wear [2].

Texturing, unlike surface finishing, is recognized as a technique that gives products not only aesthetic properties, but also offers functional properties. The texture that is provided to any surface has largely biological inspiration since the possibilities offered by biomimetics in most fields of science are widespread [8, 9].

Therefore, surface texture and its measurement are becoming the most critical factors and important indicators of functionality in the performance of high precision and nanoscale devices and components. What has influenced metrology surfaces as a discipline, making that in recent years has experienced a great paradigm shift, moving from profiles to the characterization of areas, from stochastic surfaces to structured surfaces and geometry with simple shapes to increasingly complex shapes, all on millimetre and nanometric scales [10, 11]. The texturization of surfaces allows to characterize improvements in many aspects of the technical field, such as the improvement of the performance of coupling components as bearings, improving their operation and reducing their wear thanks to the possibility of retaining the lubricant, or a longer duration of medical implants with an optimized design.

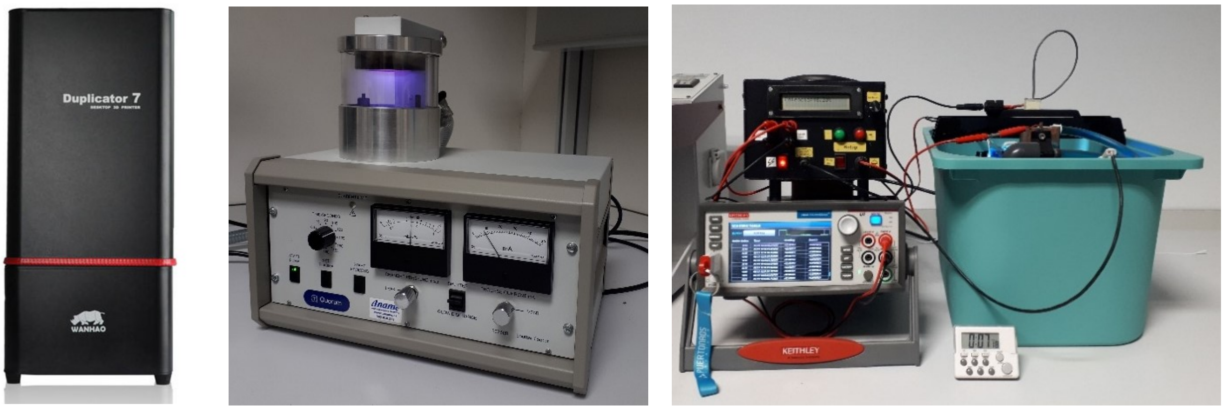
Such metrology of surfaces, we can understand it as the science that measures the small-scale geometric characteristics of surfaces, which is understood, as the surface finish in terms of microgeometric topography. Since its inception, this field of metrology has been of great importance, because it relates to disciplines such as machine tool control and manufacturing processes, and surface engineering. Now it has become more important because the industrial adoption of additive manufacturing technologies allows to increase the complexity of the surfaces generated which represents new challenges in the measurement processes [12, 13].

However, one of the biggest problems for measuring equipment's that allows us to perform this type of metrological characterizations, is the wide range of textures obtained both in the different manufacturing processes and those intentionally designed to achieve a special function. Therefore, new, more specific and versatile measuring equipment has had to be developed to perform different types of surface analysis according to the textures required.

For this reason, different measurement techniques will be used to perform the metrological characterization of microtextures, present in elements that will be used as tools in unconventional manufacturing processes. These elements are EDM electrodes, tools used in the EDM process. These electrodes have gone through several manufacturing processes to obtain their final shape, so the accumulation of errors throughout the different processes is an important factor to consider. This research has sought to identify the potential capabilities of this novel methodology for the development of these tools.

Materials and methods

This work focuses on evaluating the accumulated error in the manufacture of microtextured electrodes for the electro-erosion by penetration process (SEDM). The manufacturing process consists of several phases. First, the design of the electrode in a CAD software, which is manufactured a posteriori by means of additive technology in stereolithography by mask (MSLA), whose capabilities allow to generate the desired textures at micrometric scale, Fig. 1. It is then metallized on the part on its active surfaces by the sputtering process; and finally the part is introduced into a copper electrolytic bath by subjecting it to an electroforming process, resulting in a copper shell with its own integrity and variable thickness that becomes the textured tool used in the EDM process when assembled into an electrode holder specifically designed for this application [3].



a) b) c)

Fig. 1. a) Additive stereolithography manufacturing equipment Whanhao Duplicator 7; b) Sputtering equipment; c) electroforconformed equipment.

To obtain the final tool different manufacturing processes are required, implying an accumulation of deviations from the CAD model, which requires an analysis. Therefore, due to the need for analysis of the process stages, a metrological characterization study of the different stages of the process was carried out using different measuring equipment available in the Metrology Laboratory of the University of Cadiz, that we will proceed to describe.

First, the Leica S9 E stereo microscope has been used to perform a first optical inspection of the electroconformed shells that have been made and that thanks to their performance have allowed to obtain very sharp images captured at the perfect time, even when taken at the maximum speed as seen in Fig. 2a [14].

Subsequently, the variable focus microscope Alicona InfiniteFocusG5+ was used, which is a precise, fast, universal 3D optical measuring instrument used in the micrometric and submicrometric range. It allows to measure multiple geometric characteristics in high resolution, regardless of the material and the finish of the surfaces to be evaluated, specifically it has a maximum vertical range of 10 nm and the minimum measurable roughness of the order of 0.03 µm. This equipment combines the functionalities of a roughness measuring system with the characteristics of a coordinate measuring machine at a very local scale, Fig. 2b. Its vibration-insensitive design and the technology used ensure accurate and reliable measurements, even under workshop conditions alongside working machine tools [15].

a) b)

Fig. 2. a) LEICA Stereo microscope-head S9E. b) Variable focus microscope Alicona InfiniteFocusG6.

In the operation with this equipment, it was observed that the model parts could not adequately measure the height of some geometric elements of the textures analyzed due to their degree of transparency. It was decided to generate a negative geometry with an opaque Plastiform bicomponet putty model P80 Ra. It was observed that the ability to replicate the details of textured surfaces was very high, with a maximum reproducibility accuracy of 0.001 mm as indicated in their technical specifications, allowing to validate this indirect measurement process.

The 8 textures are those shown in Fig. 3 that differ in aesthetic details and in other cases in functional textures at different scales and shapes. Measurements of up to 8 variants were made, focusing on the results section in only two of them. This is because an inbound geometry of hemispherical microcavities has been selected for tribological applications and a protruding geometry with biomimetic overhangs inspired by shark skin texture for hydrophobic applications, to analyze how the accumulated error affects each of them, especially in the additive manufacturing process, which is where the designed geometry can be most affected.

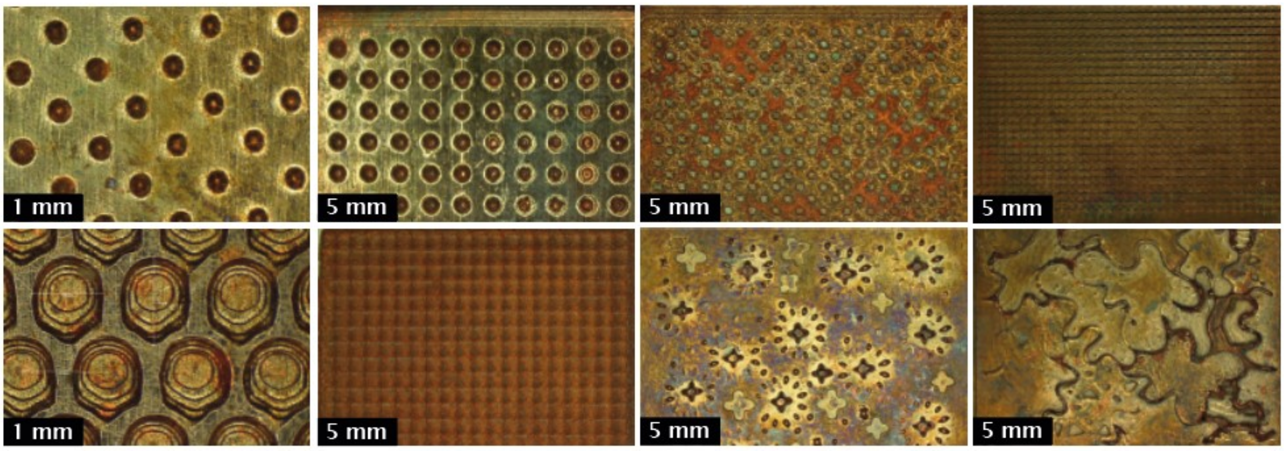


Fig. 3. Visual replicability inspection with electroforming process of electroforming shells.

Results

With the stereoscopic microscope, a first visual analysis could be made to observe the level of reproducibility of the parts in 3D printing with respect to the part designed in CAD and on the other hand the analysis of replicability of the electroforming process with respect to the part metallized model as seen in Fig. 4. Measurements were taken of both model parts and electroforms, showing very good reproducibility, Fig. 4, where the difference in the measurement in the outer circumference is 3 microns and in the inner half-sphere around 20 microns, probably as a result of resin residues in the copper shell extraction process. This shows that the metallization process of model parts when working with submicrometric values does not affect the reproducibility of the electroconforming process [16]. However, if a lack of uniformity in the thickness of the shells is highlighted as a disadvantage of the electroforming process as reflected by other authors Yang B, Leu MC, aspect to be studied in the future [17].

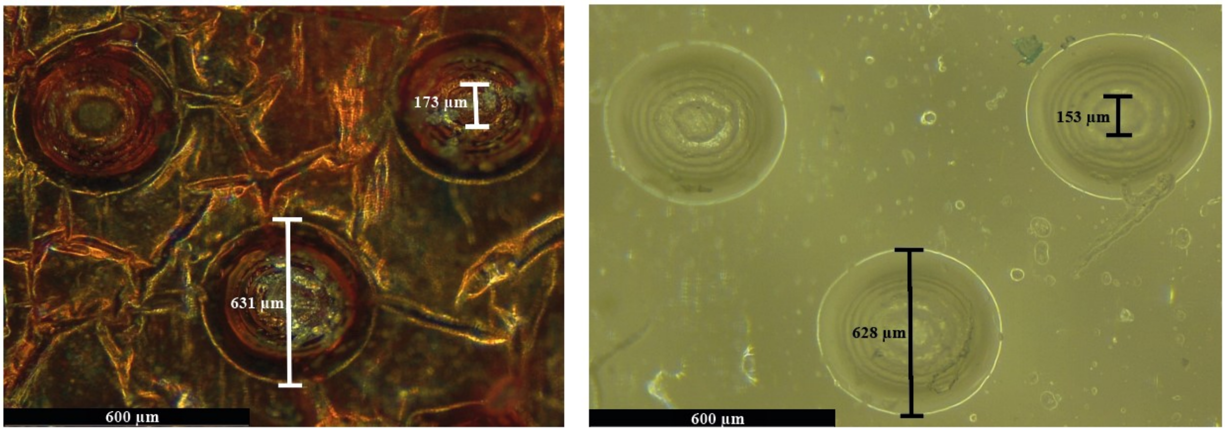


Fig. 4. Texture analysis of low relief semisphere in resin model piece and copper shell.

This equipment allowed the analysis of the model parts, although they were of a semi-transparent material and allowed to check the level of replicability of the electroforming process, observing a difference of few microns between the quantities in the shells and in the model parts. The quality of the image is so high, that sometimes it was possible to observe some small fiber that was trapped between the successive layers of the model piece.

Fig. 5 shows the design of the model parts. The central part is the area where the different textures will be generated, and the rest of the geometric details are required to facilitate deposition, to assemble the shell on the electrode holder and to establish the essential electrical connection in the electroforming process.

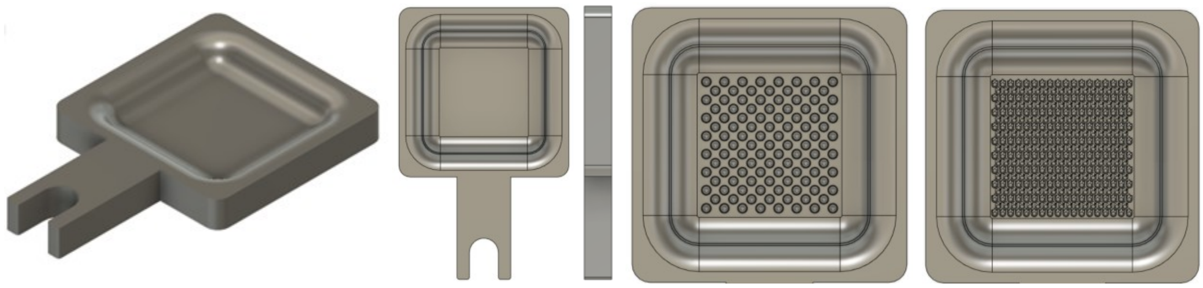
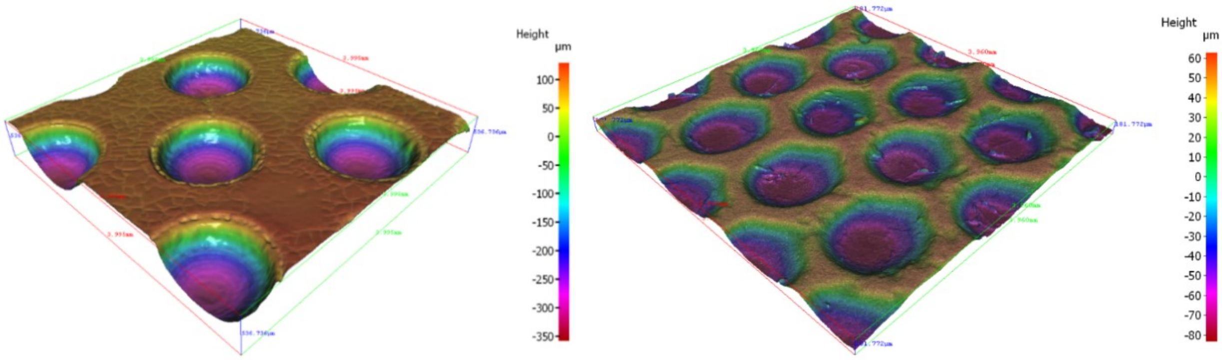


Fig. 5. Model part design where different textures will be applied.

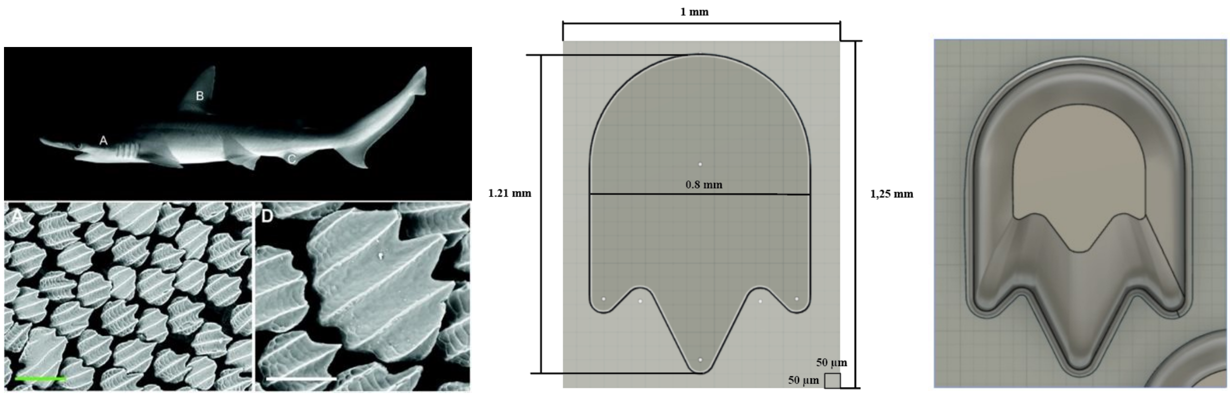
In the central part of this base electrode represented in Fig. 5 different textures were finally generated, some with a more functional character and others with a more aesthetic character. The two examples shown in this study refer to functional textures: one of them composed of low relief semisphere. Fig. 6a, which allows the retention of the lubricant, allowing less wear and friction in elements with relative movements between them. The other has a bioinspired design of shark scales, Fig. 6b, which has the function of repelling almost any substance in liquid state, thus preventing dirt from sticking to the skin of the animal, in addition to providing hydrophobicity to the surface.

The bioinspired shark skin texture was designed with some simplifications but trying to reflect the flake design. The main longitudinal dimension "c" of the designed shape is 1.21 mm, and the actual dimension of these shapes is variable, as seen in Fig. 7, with the highest proportion of them between 150 and 400 micrometers. It has been designed on a larger scale because the screen of the machine that has been used to manufacture the model parts in this study is of average performance, with a pixel resolution around 50 micrometers. During the investigation, different tests were carried out to determine the minimum print size in which an acceptable geometric definition is maintained with this equipment. It was determined that an appropriate value would be of an area of 1x1 mm2 that materializes in an array of 20x20 pixels. This is why it has been decided to work with a similar size to reflect the bioinspired texture. Similarly, the designs should avoid sharp edges, uncontrolled thickness concentrations in the electroforming and because this additive technology tends to generate rounded edges due to overexposure of resins.



a) b)

Fig. 6. a) Design of functional texture composed of low relief semisphere; b) Design of functional texture bioinspired by shark skin (study of replica putty).

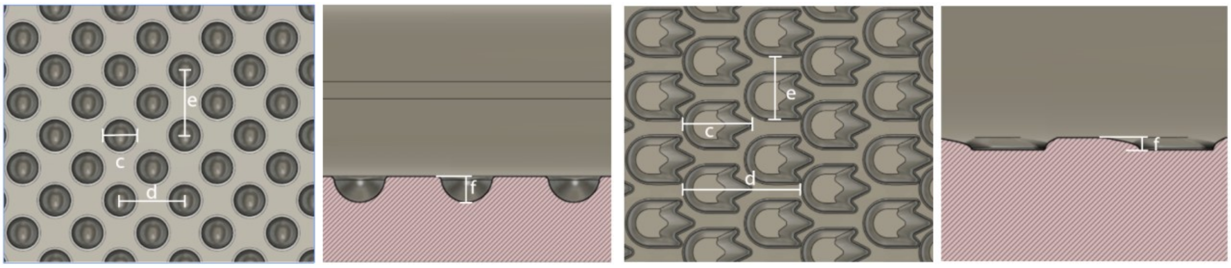


a) b) c)

Fig. 7. Shark skin texture: a) green scale 200 micrometers, white scale 100 micrometers. Modified figure [18]; b) 50 x 50 micrometers scale representation; c) decentralization of scale manufacturing in 3D printing.

Dimensional deviation study

To calculate the accumulated error in the manufacturing process of the electroconformed electrodes, it is necessary to make tables analyzing the dimensions of all the necessary steps until reaching the final product. Therefore, Fig. 8 show the significant measures that will be taken, to analyze the replicability of each stage and the accumulated error at the end of the process. In the case of measure c of the shark skin microtextured electrode, this direction has been selected because it is considered to be the most variable in relation to the nominal value established in the CAD.



a) b)

Fig. 8. a) Electrode with microtexture of low relief semisphere. Measurements to be analyzed; b) Electrode with microtexture of shark skin. Measures to analyze.

For the metrological characterization of the dimensions reflected in the previous figures it is necessary to make use of a specific software in this field. For that reason, this study used MountainsMap, a 3D surface microtopography analysis software developed by Digital Surf. Fig. 9 shows the result of the scanners of the different textures. This powerful tool allows to analyze the point clouds that represent the different textures collected using the Alicona devices.

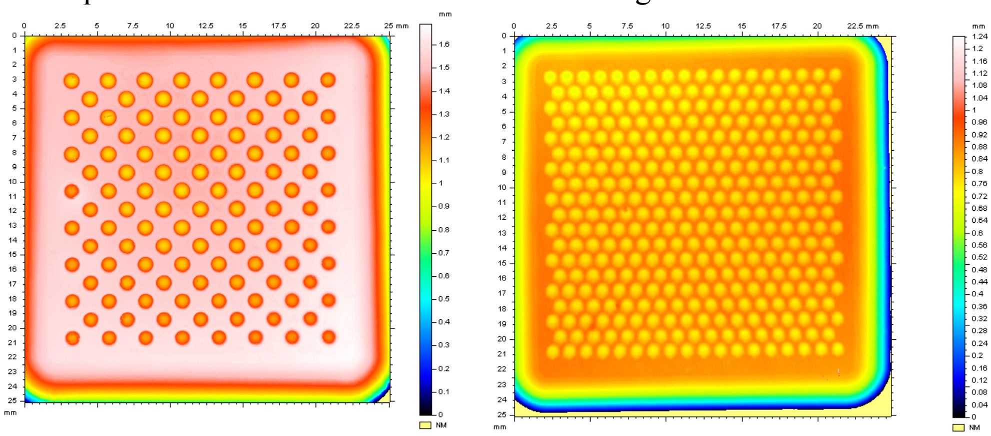


Fig. 9 Analysis using the MountainsMap software: a) texture of low relief semispheres; b) texture of overemphasized shark skin.

Using this software, you can determine each of the required dimensions, in addition to being able to perform different types of shape and roughness analysis. In Tables 1 and 2, the variations of the reference quantities at each stage are analyzed, from the CAD model to the electroeroded part, through the electroconformed shell used in the electroerosion process, calculating at the end the accumulated error in each of the analyzed quantities.

Table 1. Metrological characterization of the low relief semisphere texture generation process.

Low relief semisphere texture										
		PHASE 1: P.M.			PHASE 2: C.C.			PHASE 3: P.E.		
D [mm]	CAD [mm]	Av. [mm]	S.D. [mm]	Error 1 [mm]	Av. [mm]	S.D. [mm]	Error 2 [mm]	Av. [mm]	S.D. [mm]	Error 3 [mm]
c	1.2	1.142	0.038	0,058	1.111	0.014	0,089	1.149	0.020	0,051
d	2.5	2.509	0.010	-0,009	2.515	0.015	-0,015	2.518	0.009	-0,018
e	2.5	2.513	0.011	-0,013	2.515	0.012	-0,015	2.508	0.017	-0,008
f	0.6	0.401	0.014	0,199	0.458	0.021	0,142	0.443	0.004	0,157
D: Dimension; P.M.: Model Part; C.C.: Copper shell; P.E.: Eroded piece; S.D.: Standard Deviation; Av.: average; Error 1 = CAD – Av.P.M.; Error 2 = CAD – Av.C.C.; Error 3 = CAD – Av.P.E.										

Table 2. Metrological characterization of shark skin textures generation process.

Shark skin texture														
			PHASE 1: P.M.				PHASE 2: C.C.				PHASE 3: P.E.			
D [mm]	CAD [mm]		Av. [mm]	S.D. [mm]	Error 1 [mm]		Av. [mm]	S.D. [mm]	Error 2 [mm]		Av. [mm]	S.D. [mm]	Error 3 [mm]
c	1.21		1,042	0,031	0,168		1,056	0,029	0,154		1,065	0,032	0,145
d	2.00		2,047	0,021	-0,047		2,051	0,016	-0,051		2,040	0,014	-0,040
e	1.10		1,136	0,020	-0,036		1,119	0,037	-0,019		1,117	0,027	-0,017
f	0.15		0,128	0,005	0,022		0,139	0,005	0,011		0,131	0,004	0,019
D: Dimension; P.M.: Model Part; C.C.: Copper shell; P.E.: Eroded piece; S.D.: Standard Deviation; Av.: average; Error 1 = CAD – Av.P.M.; Error 2 = CAD – Av.C.C.; Error 3 = CAD – Av.P.E.														

The results shown in the table are the average values of 10 measurements and their corresponding standard deviations, taken for each magnitude in the central zone of the textured area. These measurements were made with the MountainsMap software, taking measurements at points distributed along the textured surface. Although it is a manual procedure subject to the visual appreciation of the person performing the measurement, it is observed that the highest value of the standard deviation is 0.038 mm, which is less than the pixel size of the MSLA equipment.

From these results it can be observed that the error in the parameter "c" that sizes the shape of the element that generates the texture is much greater than the parameters "d" and "e" which establish the lateral step positioning of both textures in the XY plane of manufacturing layers. These three parameters are significantly higher in shark skin texture due to a worse definition of its irregular shape, compared to the regular shape of a circle used in the texture of semispheres. Regarding the error in the parameter "f" it is considered that it is much higher in the texture of semispheres because in the model piece it materializes with a low relief. The bottom of the semisphere is formed in the first manufacturing layers, which causes the resin to be trapped and subjected to overexposure in the following layers. In the texture of shark skin, the element that generates it is in overrelief, and the bottom is generated in the last manufacturing layers of that area, in addition the liquid resin has more space where flow more easily and does not occur that phenomenon.

For these reasons, it is considered that the production of the model part using MSLA technology is the one that contributes a higher percentage of the accumulated error in the process chain applied for the manufacture of these electrodes. In addition, another factor that affects the dimensional change is the deformation of the microtextures, this is due to the resolution of the screen of the 3D printing machine. This resolution is approximately 50 µm per pixel and since one of the textures does not fit well in the pixel matrix, as the production of layers progresses a small distortion may increase in magnitude, generating in some cases the deformations of the geometries designed. This effect seems to be more accentuated in geometry of greater complexity, as geometric details of magnitude are closer to pixel size. However, it is also important to note that the dimensions of the electroformed electrode have values very similar to those of the model part, evidencing the high replicability capabilities that allows this technology to be achieved.

Similarly, a study was made of the dimensional variation suffered by the electroconformed electrode once the electroerosion process has been performed with it, to check how the electroerosion process affects its wear. Note that the geometry of the semisphere electrode is overlaid on the surface of the electrode and generates those microcavities on the surface of the eroded part. The wear of this geometry will be in the sense of decreasing its dimensions. However, in the electrode with the texture of shark skin, the designed elements are in low relief and therefore when worn the electrode the dimensions would tend to increase.

Table 3. Analysis of wear of electroform after erosion of both textures.

Dimensional values of hemispheres textured electrode			Dimensional values of shark skin textured electrode		
Unused electrode	Electrode after eroding	Wear	Unused electrode	Electrode after eroding	Wear
c = 1.111 mm	**c** = 1.149 mm	**-0.038 mm**	**c** = 1.056 mm	**c** = 1.065 mm	**-0.010 mm**
d = 2.516 mm	**d** = 2.518 mm	**-0.002 mm**	**d** = 2.051 mm	**d** = 2.040 mm	**0.011 mm**
e = 2.515 mm	**e** = 2.508 mm	**0.007 mm**	**e** = 1.119 mm	**e** = 1.117 mm	**0.002 mm**
f = 0.458 mm	**f** = 0.443 mm	**0.015 mm**	**f** = 0.139 mm	**f** = 0.131 mm	**0.008 mm**

As can be seen, the reference quantities have been modified very few microns due to the fact that the EDM procedure was done under finishing conditions with very low VDIs to minimize tool wear. In some of them the sense of wear mentioned above has been maintained but in others values are obtained in the opposite direction, possibly due to small dimensional variations caused by the temperatures to which the electrodes are subjected during the EDM process, and also by the adhesions of small amounts of the eroded material on the electrode surface. It is claimed, therefore, like authors such as Yarlagadda et al. that electroformed copper electrodes show good potential for use as EDM tools although their use in roughing operations is not recommended [19].

Only the first erosion of the electrode has been analyzed in which the small surface irregularities that may have remained in the elaboration of these tools are usually attenuated. It is because electrical discharges are concentrated at these points at the initial moments of the process, and they also generate the small roundings of the sharp edges. Once the electrode surfaces are smoothed, the current distribution on their surfaces will be more homogeneous in the following operations with the electrode and their wear will be lower and progressive.

Conclusions

This research confirms that the generation of microtextured electrodes for EDM through the combination of low-cost additive manufacturing processes and copper electroforming process are more efficient and less expensive compared to conventional processes used to date. Fully functional tools are achieved, which can generate surface textures at the micrometric level of geometries almost impossible with other technologies such as machining and which can also be generated in relatively short periods of time compared to other alternatives.

The great replicability of the particular electroforming process and the set of processes used to generate these EDM electrodes is evident. It has been possible to quantify the dimensional deviations in the different phases of the process which allows to contemplate them in the initial phases of the design of the electrode to achieve more demanding levels of precision in the texturization of surfaces.

In general terms it has been observed that the variation of reference quantities is relatively small being the process that generates the greatest source of errors additive manufacturing with MSLA technology. This aspect can be improved by making use of existing equipment on the market with better screen resolution, although logically with higher acquisition costs.

After a simple analysis at the initial wear of the electrode after an EDM test, the need for a more detailed analysis with a large number of tests has been identified to evaluate the progression of wear in successive EDM processes, and under different process conditions. This would allow the useful life of this type of electrodes to be determined according to the precision required in the textures, or the minimum thickness of electroformed shell required depending on the application and expected life of the electrodes.

Likewise, an improvement for the following studies is to support the copper shells by filling the back of them before extraction, thus avoiding possible deformations.

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