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Short Communication

Photolithography – Electroforming – Pulse Electrochemical Machining: An Innovative Process Chain for the High Precision and Reproducible Manufacturing of Complex Microstructures

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One benefit of Pulse Electrochemical Machining (PECM) is the residual stress-free processing of complex geometries which are difficult to produce by conventional techniques. However, a major inconvenience by applying PECM is the realization of the cathodes, when sophisticated microstructures are required. The potential of a new and innovative process chain combining photolithography, electroforming and PECM is investigated to overcome this difficulty by providing a reproducible and high precision tool manufacturing. The master microstructure is realized by photolithography and is subsequently used as template in an electroforming process to realize reproducible workpieces which serve as tools within the PECM process.

Keywords: Electroforming, Photolitography, Pulse Electrochemical machining (PECM), Rapid Tooling

1. INTRODUCTION

Over the last years, the downsizing of industrial components and the tribological optimization of their subsurface properties via microstructuring have become a major and essential issue in several industrial sectors, e.g. automotive, medicine or aerospace industry. These requirements led to an increasingly decisive role of the micromachining technologies, where the material removal ranged from some microns to millimeters [1-2]. This implies higher precision in manufacturing [3], which becomes even more challenging to reach by processing difficult-to-cut materials.

In most cases, the processing of sophisticated structures in such materials by conventional machining techniques becomes very difficult because of the induced mechanical deformation, heat generation in the workpiece and the lack of rigidity in the process, which severely degrade the machining accuracy [1-3]. Besides, the microstructuring of three-dimensional shapes remain highly complicated and limited.

Most non-conventional machining techniques, e.g. Electrical Discharge Machining (EDM), Laser Beam Machining (LBM) or Electron Beam Machining (EBM), also failed by the processing of complex microstructures because they are thermally oriented and therefore generate a distortion and deterioration of the integrity of the surface [1, 3]. Other non-conventional processes like metallic 3D-printing indeed allow a stress-, distortion- and burr-free 3D-structuring but cannot currently provide for the required accuracy [4].

Electrochemical Machining (ECM) techniques however do not influence the rim zone of the workpiece, neither by inducing thermal nor mechanical residual stresses [5-6] as the shape of a working electrode is negatively transferred on the workpiece by anodic dissolution [5-10]. Therefore, the machining occurs independently of the materials mechanical characteristics [9]. Especially Pulse Electrochemical Machining (PECM), as further development of conventional ECM, provides for high precision, high copying accuracy and reproducible machining of complex shapes and structures due to the slight interelectrode gaps which can be reached during the process [5-10].

The main problem of the PECM technology is the machining of the working electrode. Indeed, the tool has to be realized with other manufacturing techniques, whether conventional or non-conventional, implying that the above mentioned problems occurs again.

In this contribution, the potential of an alternative process chain combining photolithography and electroforming for the production of PECM tools and also the high precision and reproducible microstructuring of components by PECM are presented. Using shadow projection structures with aspect ratios of up to 10, lateral dimensions down to some micrometers and heights of up to several hundred micrometers can be produced by photolithography [11]. Subsequently, the resist structures are electroformed with nickel, wherein the desired profile depth of the structure can be adjusted by the resist thickness. The galvanic build-up microstructured part is used as tool in the PECM process. Thus, the electrode can finally be used for the series production of microstructured components with all advantages of the PECM procedure.

2. DESCRIPTION OF THE PROCESS CHAIN

2.1. Manufacturing of the master form by Photolithography

A new technique linking different research areas was developed for producing PECM tools. The process chain of this new technique is presented in Fig. 1.

The following paragraphs give a detailed overview about the different steps of the method. After every step, a characterization of the resulting structure is performed in order to validate the process. At the beginning of the process chain a standard photolithographic structuring takes place, followed by manufacturing a bath model and a galvanic deposition process for tool forming. Then, this electroformed tool can be used for the PECM process.

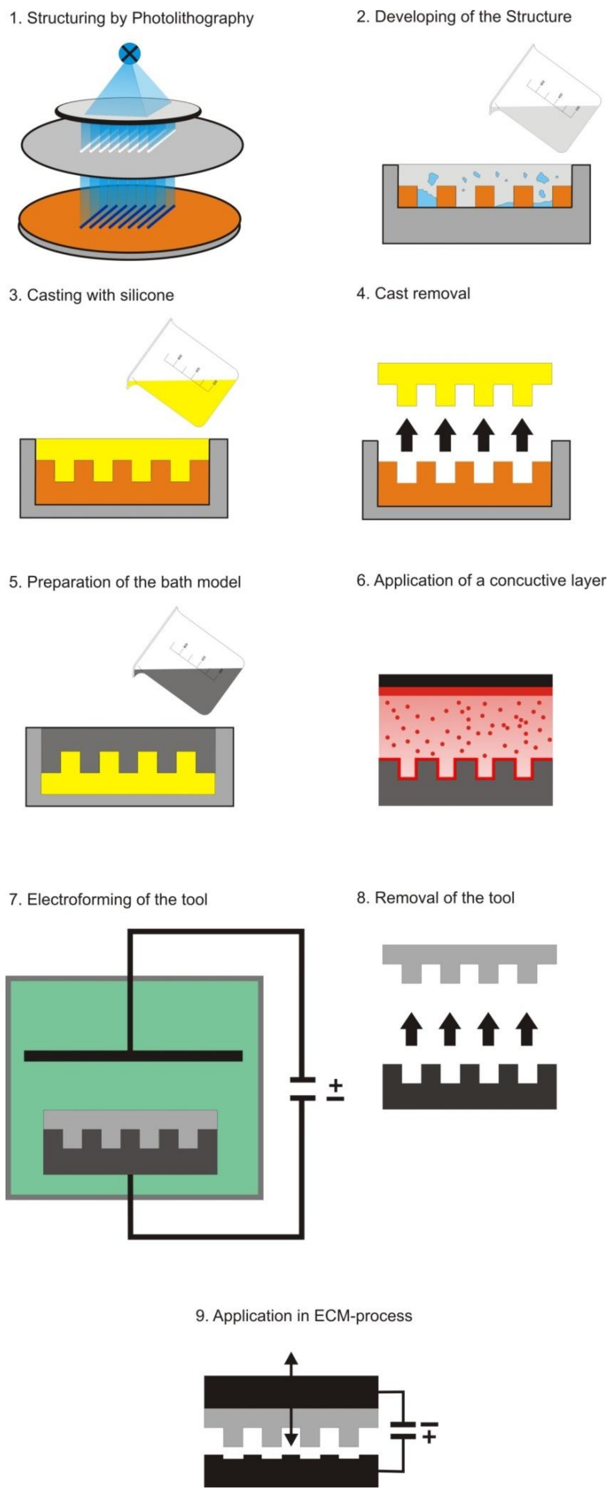

Figure 1. Scheme of the process chain

The master patterns are produced by a 1:1 shadow printing process. The process scheme is shown in Fig. 1, steps 1 and 2. The mask consists of a transparent quartz carrier and of light absorbing chromium line structures. The liquid photosensitive resist is casted by spin coating onto a silicon wafer. A baking step is necessary to remove most of the solvent, getting a relatively stable resist layer. Then, the pattern of the mask is transferred to the resist by imaging with a mercury vapor lamp. The solubility of the imaged resist areas are decreased due to a photo-induced chemical reaction. Finally, the resist areas, which have not been exposed by light, can be dissolved in a developer solution. The final resist patterns consist of the exposed resist.

As resist the AZ 125nXT (MicroChemicals, Ulm, Germany) negative resist is used. To get a homogeneous, crack-free resist layer of 43.2 µm a five step spin coating process followed by a soft baking process was applied. For spin coating spin speeds of 0, 200, 400, 600 and 500 rounds per minutes, applied for 32 seconds each step, were used. During the last spinning step, the edge of the wafer was rinsed with a solvent to get rid of the relatively higher resist at the edge region of the wafer. One temperature treatment was performed at 135°C for 20 minutes, followed by another at 22 °C for 120 minutes for relaxation of the resist.

The exposure of the resist was done with hard contact modus using an exposure time of 800 seconds with a dose of 5.9 mW/cm². To get the final resist structures (Fig. 2, left) the wafer is immersed in an alkaline developer solution (AZ 726, TMAH-based, MicroChemicals, Ulm, Germany) for 3:50 minutes, followed by rinsing with water for one minute.

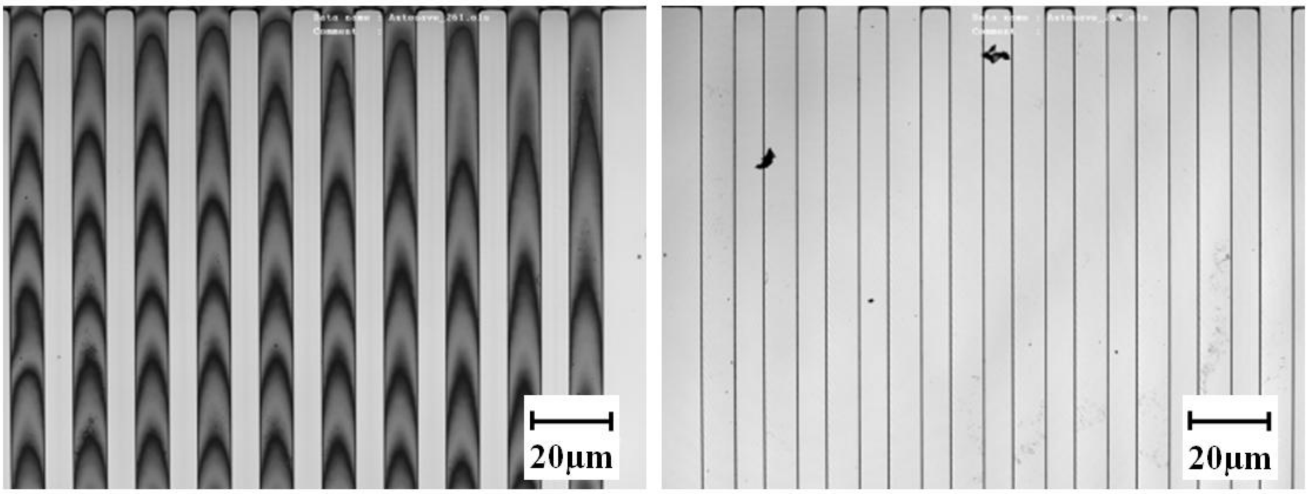

Figure 2. Final resist structure (left) and silicone profile (right)

2.2. Transfer of the master form to a bath model

The structure gained by the abovementioned photolithographic process (Fig. 1, steps 1, 2) is used as a master form for the further procedure. This master template is the starting point for the manufacturing of bath models described in literature [12]. In a first step, a negative form of the master structure (Fig. 1, steps 3, 4) is produced. Therefore, liquid in a desiccator degased silicone, was casted over the structure. During this step, the silicone molds every detail of the master form. This negative silicone profile (Fig. 2, right) is used for manufacturing the so-called bath model (Fig. 3), an epoxy resin structure. This 3D structure serves as template for the electrodeposition process.

During the production process of the bath model, different layers of an epoxy resin were put on the silicone profile (Fig. 1, step 5). It is a multi-step process with three resin layers, completed with a composite of epoxy resin and glass fibers for mechanical stability. This bath model has to cure for about 24 hours. After this time, the surface of the bath model is sputtered with a metal layer to ensure the electrical conductivity (Fig. 1, step 6). In this case, a gold layer of a few nanometers thickness which does not affect the surface topography was used.

In a last step, the sputtered bath model (Fig. 3) is wired and different shieldings are added for a more homogeneous deposition process. Subsequently, the bath model is dipped in the galvanic bath for plating a thick nickel layer (Fig. 1, step 7).

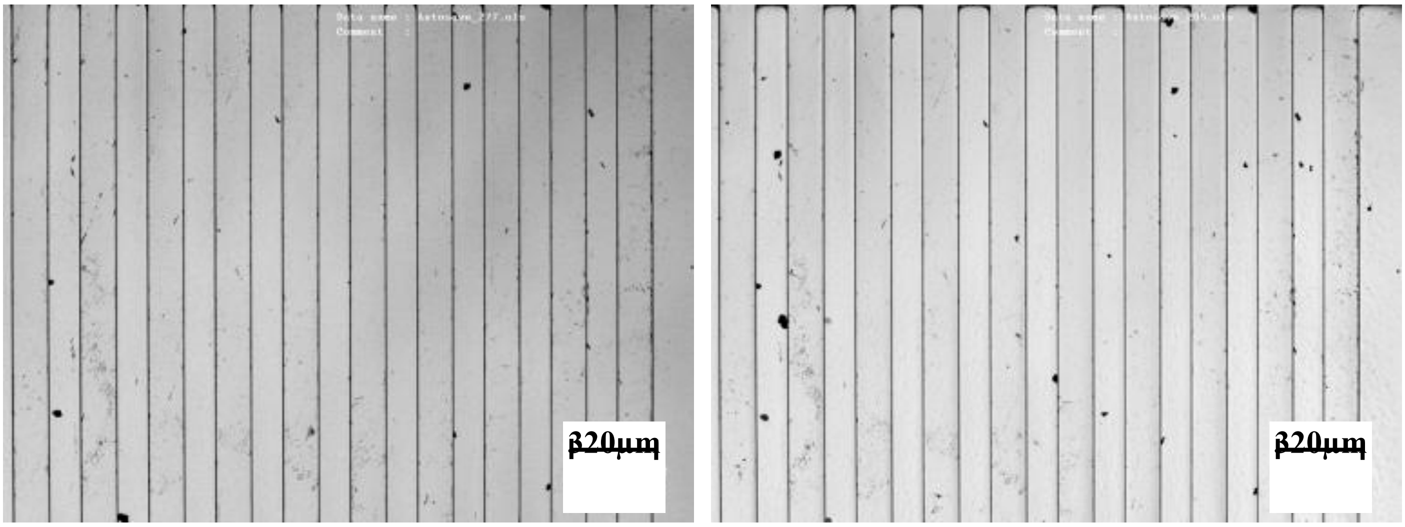

Figure 3. Bath model (left) and sputtered bath model (right)

2.3. Electroforming process of the PECM-tool

For the deposition of nickel on the created structures, a commercial nickel sulfamate electrolyte was used. In a lab scale bath of 4-L volume, the electrolyte was tempered at 40 °C and the pH was adjusted to 3.8. The deposition process was performed under current control with a two electrode setup (Fig. 1, step 7). The current density was set to −20 mA/cm². The conductive bath model is the working electrode, and a sacrificial anode consisting of a nickel-filled titanium mesh is the counter electrode. The deposition rate at the abovementioned parameters is about 23 µm/hour. The current efficiency of the applied electrodeposition is 97%. To use the deposited nickel geometries as a PECM-tool (Fig. 4), a thickness of at least 4 mm is required. So, a typical tool deposition takes about one week. By adding different additives like grain refiners and levelling agents, the material parameters of the deposited nickel can be tailored.

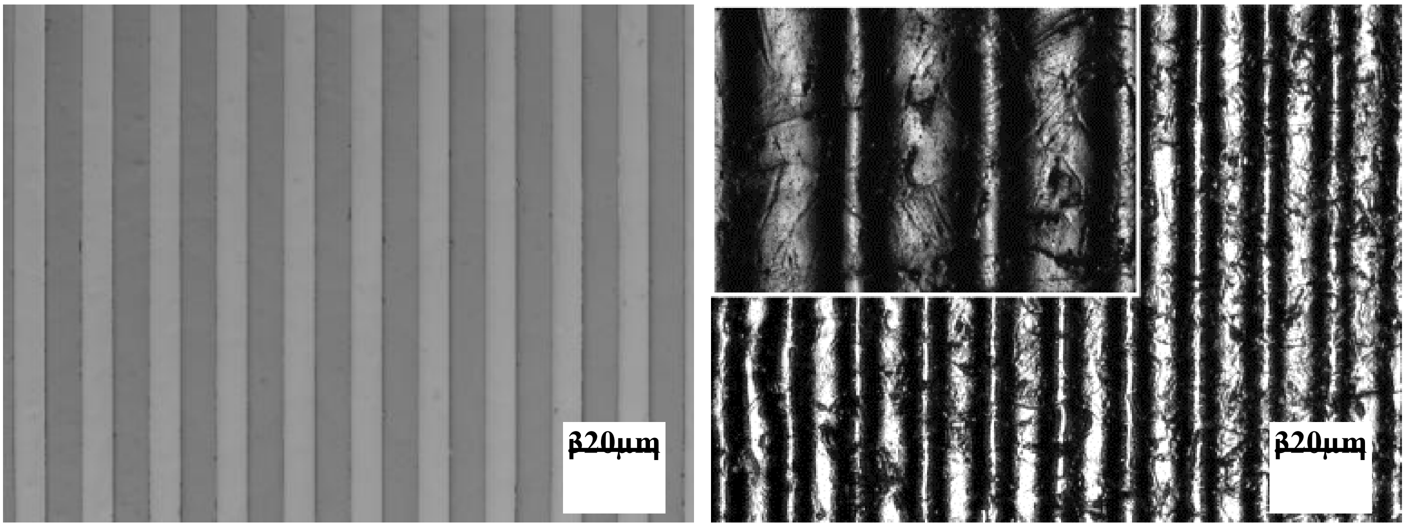

Figure 4. Tool (left) and PECM-machined workpiece (right)

2.4. PECM-microstructuring with the electroformed PECM-Tool

The processing was conducted on an industrial PEMCenter8000 (PEMTec SNC, Forbach, France). The electrolyte used for the investigations was a solution of NaNO3 tempered at 21°C with an electrical conductivity of 70 mS/cm at pH 7.

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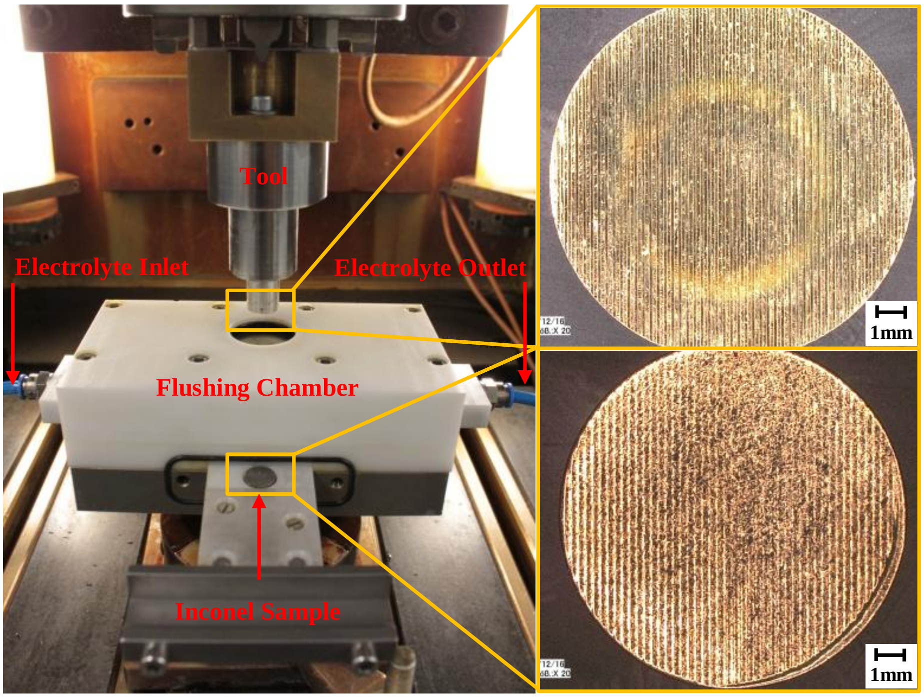

Figure 5. Experimental set-up used for the microstructuration

The electrolyte was side-fed in a flushing chamber. The initial interelectrode gap was set to 20 microns. In a first step, the tool travelled 50 microns from its initial position with a feed rate of 0.15

mm/min, a voltage of 11 V, a vibration frequency of 50 Hz, a pulse on-time of 2 ms and an electrolyte flow rate of 4 L/min. In a second step, it travelled 10 microns more with a pulse on-time reduced to 1.2 ms and a feed rate increased to 0.2 mm/min.

The microstructuration was performed on a commercially available nickel-based-superalloy, INCONEL 718 (Fig. 4). The experimental set-up is shown in Fig. 5

3. RESULTS AND DISCUSSION

3.1. Shape monitoring during the tool manufacturing process

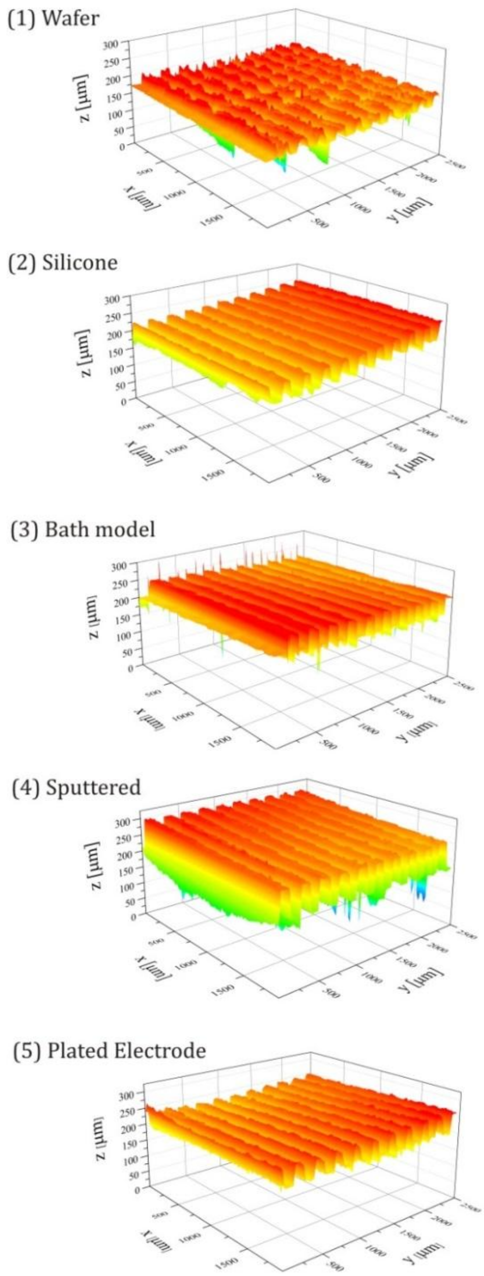

Figure 6. 3D-scans of the surfaces obtained during the process chain

Each step of the production process was monitored by a laser scanning microscope LEXT OLS 3100 (Olympus, Hamburg, Germany). The results are shown in Fig. 6.

The resulting shape parameters of different strips determined from the 3D scans are summarized in Table 1.

Table 1. Shape analysis during the process chain

Process step	Strip width [µm]	Strip height [µm]
Wafer (1)	110.8 ± 0.5	43.2 ± 5.7
Silicone (2)	111.4 ± 2.0	46.1 ± 2.2
Bath model (3)	121.3 ± 1.4	44.9 ± 2.3
Sputtered (4)	115.9 ± 2.4	46.0 ± 1.8
Plated electrode (5)	113.4 ± 1.7	46.2 ± 3.0

It can be seen that for every step of the chain a high accuracy is achieved. In order to prove this behavior, the structure was gauged at least at nine different points (Fig. 7) and the average and standard deviation of these values were determined. The deviation between the photolithographic and the resulting plated structure is about 2.6 µm in width. Due to light reflections on the surface, the laser scanning microscopy cannot resolve the details of the initial structure on the copper sputtered silicon wafer (Fig. 6, 1). For this reason, a cross-section of the line structure was prepared and measured by high resolution light microscopy (Nikon SMZ 800, Nikon GmbH, Düsseldorf, Germany). Over all steps during the fabrication a very homogeneous height distribution with a deviation of 3.0 µm can be observed.

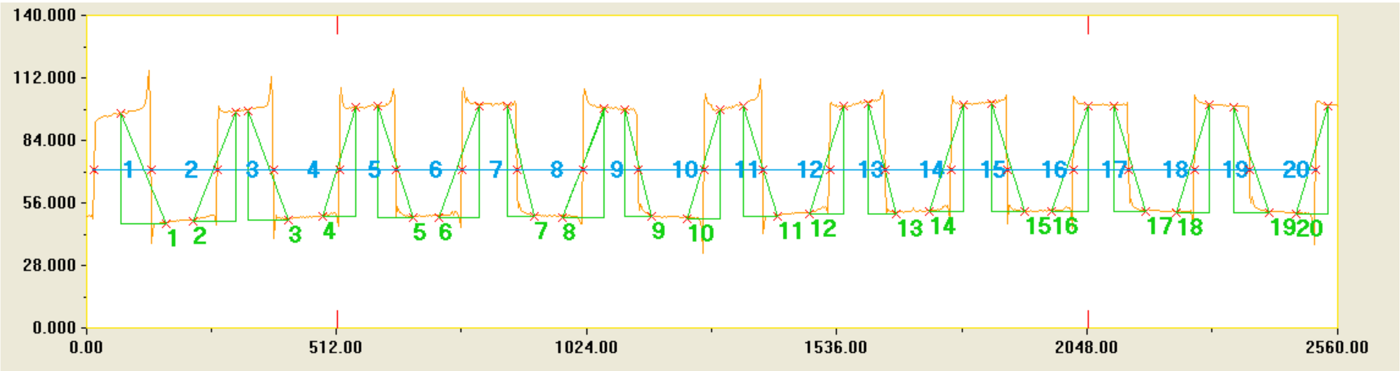

Figure 7. Strip width (blue) and height (green) measured for the tool

3.2. Characterization of the final structures

The microstructure obtained after processing under PECM conditions is shown is Fig. 8. The shape of the Inconel sample after machining slightly differs from that of the tool. The strip edges are rounded out so that the strip does not remain perpendicular but has an angle of approximately 70°. The average strip width behaves 60 µm at the top and 123 µm at the bottom. This difference compared to the 113 µm of the tool is due to the front and lateral gap which develop during the material dissolution and are inherent to the PECM process. The strip height averages 35.8 µm which complies with the set 40 µm height from the initial surface of the workpiece as described in Sec. 2.4.

As expected, there are several problems with perpendicular structures. Due to limitations of the PECM process it is not possible to reach a complete congruent copy of the tool. There are always some deviations between the photolithography and the final work piece. Fabricating microholes with micro-ECM, Mithu et al. showed that there is no perfect perpendicular flank angle [13]. They also received an inclined wall surface. Indeed this is a problem especially for machining small structures like these ones in the present investigation. Kozak et al. observed this behavior already some years before [14]. The smaller the dimensions of the structures used for the PECM process the bigger is the influence of this bevel.

To get perfect perpendicular structures in the resulting work piece, a modification of the tool is necessary. There are two possible routes which could be suitable for a modification of the tool. First route is the insulation of the perpendicular sides of the tool. In this case the removal of the work piece will take place at the face side of the tool structure. A second way would be a new shape of the tool geometry optimized for the resulting structure, revealed e.g. by computer simulations [15]. The adjustment of the master form to match the required final sample structure will be investigated in further works according to the inverse problems of shaping during PECM [14, 16, 17].

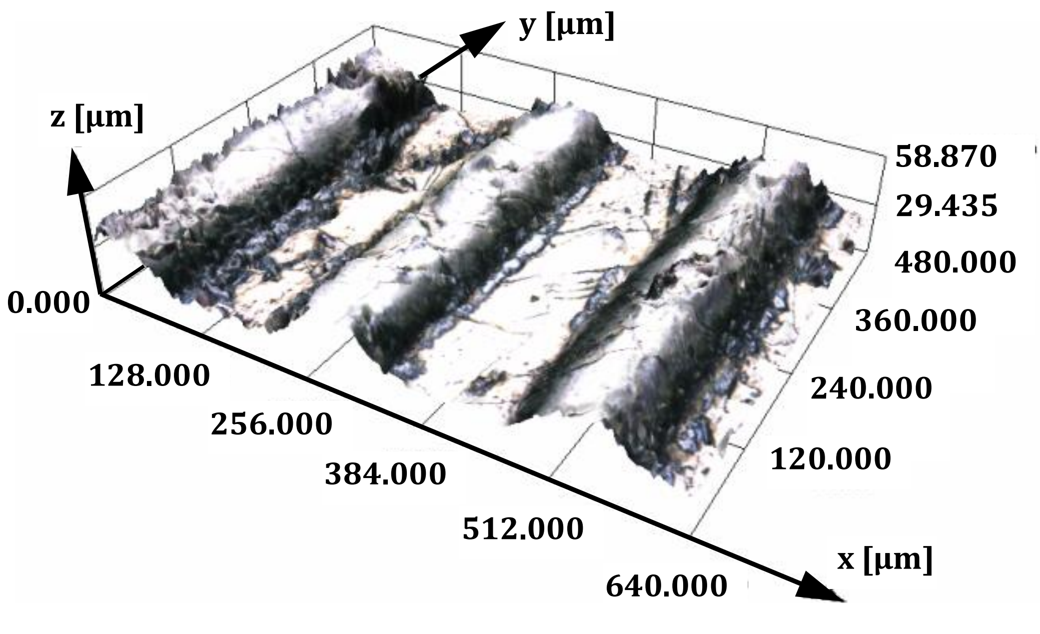

Figure 8. 3D-Microscopy of the PECM-machined microstructure

4. CONCLUSION AND OUTLOOK

A new procedure based on photolithography for the manufacturing of PECM-tools is presented. In contrast to the well-established LIGA method [18], the combination of photolithography and electroforming is not so far used for the production of tools for electrochemical machining applications. A technology transfer from microsystems technology takes place to the tool formation for electrochemical machining purposes and so all benefits and know-how in these areas can be used. A new process chain consisting of steps which combine very easy performing and low costs with a high tool precision and a very good reproducibility is established. Further advantages are flexibility of structure geometries and short manufacturing times. The tool dimensions can be continuously scaled up to a diameter of 200 mm. After designing a tool, the CAD-construction can be used for the photolithographic process. The feasible structural dimensions of a tool range from sub-micrometer to some millimeters. The photolithographic process is the basic step of the production chain because the initial geometries were formed. The shape (aspect ratio, depth, profile) of the tool structures can be influenced and controlled by the process parameters.

These new possibilities of tool structuring enable quite new PECM applications in manufacturing technology. New scales of structures can be realized by this procedure. Using conventional manufacturing technologies these scales cannot be reached or only by cost-intensive production steps. So a new field of application for PECM process can be gained by this kind of tool production. Since the final shape of PECM-tools is currently still determined iteratively [14,16,17], implying the manufacturing of several intermediate electrodes, the presented production route could prove to be preventing the highly expensive realization of these electrodes by conventional processes. This process chain is also suitable for the series production of tools. If a silicone cast once was manufactured it can be used as template for the production of identical tools which can be used for parallel PECM-processing. In the case of a high tool wear, e.g. by a bipolar machining, the PECM process becomes very expensive. In this case, the series production of cheap tools makes the process more economic. The preparation of the bath model, the application of a conductive layer and the electroforming process itself require relative cheap equipment which can be installed besides a production line. The tool production process itself does not need very highly trained experts. The processing and the demands on human resources are responsible for a very high economic benefit.

A modification of the presented method enables the duplication of existing tools which were formed by expensive mechanical processes. In this case, the tool can be used as template for the production of the silicon cast. The economic benefits are the same as discussed before.

These recent results and the further development of this new tooling process will maintain future application and possibilities of the PECM technique.

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