Investigation on the Effectiveness of Through-hole Replicas of Deep Small Holes

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When a micro-hole of high aspect-ratio is required, in addition to machining problems, special attention should be paid to controlling the quality of the manufactured products. Dimensional and surface metrology in the field of micromachining can be as critical as machining itself, therefore several new measurement methods have been developed. However, many of these methods suffer from application limits when used in the case of a deep hole. Replication can be a useful approach, which has well-proven validity in the time-consuming case of the sectioned hole. The method of through replicas, to be pulled out of the unsectioned hole, still needs verification.
In the present paper, the surface roughness of deep small electrodischarge drilled holes is measured, and the effectiveness of the use of both open- and through-replicas is evaluated, versus direct measurements on the micro-drilled surfaces. Through-hole replicas, by means of injection and extraction of a silicone, are proven reliable for reproducing the surface morphology of holes down to 0.8 mm diameter with an aspect ratio of 12.5. The findings show that the operative range of the considered techniques may be extended with respect to the previous cases mentioned in literature

Keywords: Electro discharge drilling; quality control; silicone replica; high aspect ratio hole; roughness measurement;

1 Introduction

In recent years, research into micro manufacturing techniques has increasingly attracted the interest of defence industries, as far as communication and micro-electro-mechanical systems are concerned. Micro manufacturing techniques include the production of micro-shafts and micro-holes, and in particular specifically shaped micro-holes and micro-slots [1,2]. If a high aspect-ratio hole is required (for example in a super alloy or a hard material), traditional machining is inadequate, due to the high risk of drill-bit failure, low level of accuracy, short tool life and scanty surface finish [3]. Micro-holes are currently drilled by means of different manufacturing methods, including: micro-EDM, electron beam machining (EBM), laser machining, etching, electric chemical machining (ECM) and micro-ultrasonic machining (MUSM) [1,3-4]. These techniques do not involve any direct contact between the tool and the workpiece, and in this way mechanical stresses are eliminated as well as chatter and vibrations.

However, when the problem of manufacturing has been solved, the next critical aspect is how to control the quality of the manufactured products. Quality control of micro-machined parts requires accurate measuring instruments and procedures [5]. Micro holes must be inspected to determine the level of form accuracy and geometrical integrity pertaining to the diameter, roundness, taper angle and true centre.

Therefore, dimensional metrology is crucial in the field of micromachining, and many new measurement methods and equipments have been developed, but most of them suffer from severe drawbacks. An original vibroscanning method for the measuring of the inside shape of micro holes was presented by Masuzawa *et al*. [5]. Their extremely interesting approach allows to measure holes with diameter as small as 127μm, but only if the aspect ratio is around 1 [5].

Additional options come from piezo resistive cantilever probes, designed for dimensional measurements with high-aspect-ratio micro components. Some authors [6,7] have reported the following dimensions of cantilevers:

- length =1.5-5 mm;
- width = 30 – 200 μm;
- height = 25 – 50 μm.

Tactile micro probe sensor concepts have been proposed and tested relying on a compliant shaft instead of a stiff one. Passive-sensing fibre-optics and vibrating carbon probes, including either a small glass sphere or a "virtual tip" as the probing element, offer very low probing forces of around 1 μN or even lower. However, the number of points per second that these techniques are able to acquire is too slow for high-throughput form and roughness measurements Not even the aforementioned solutions can be used to measure roughness along the 10 mm depth of the holes considered in the present paper. Moreover, cantilever probes allow only linear roughness Ra to be evaluated, but gives no information about surface morphology or area surface parameters like Sa. .

Section observation at the microscope is still the most common procedure that is used by many authors for the control of deep small holes [1,8-11]. The evaluation of the micro hole surface by sectioning, grinding and polishing, followed by SEM (Scanning Electron Microscope) or OM (Optical Microscope) direct observation, is a destructive and time consuming procedure.

The use of surface replicas is a technique that is frequently adopted in surface metrology. A setting compound is poured onto the area of interest; when it has cured, it can be removed, thus providing a solid surface that should ideally be the negative "photograph" of the area of interest. Morphologic data are transferred from the component surface, which may be inaccessible, to the measurement system by means of an intermediate replication step. The key requirement of the replica is that the geometric shape of the contact face should be an accurate copy of the parent surface. The replica may be difficult to remove, and can therefore require the use of a chemical release agent, which can impede replication of the fine structure. No release agent has been used in the present research.

Some authors [12] have reported that two types of information can be estimated by replication: the shape and the statistical characteristics of the a surface. The geometric data are suitable for larger components than 10 mm [12], and they require that the region over which the estimate is made has to be specified precisely on the counter face. When using statistical data for the comparison of two surfaces, instead, careful attention must be paid to the parameter chosen to describe the surface. In fact, the chosen parameter should be capable of pointing out replication errors.

The replica evaluated by means of statistical data should be taken from the whole parent surface, and it should obviously retain as much of the original profile information as possible. Statistical parameters are representative of the entire surface, and they should be capable of distinguishing replication errors. Replicas, in general, show somewhat lower roughness values than the original surface. On the contrary, the deviation of surface parameters among repeated measurements on replicas is often considerably larger than on repeated measurements of the original surfaces [13].

Several papers have investigated the fidelity of replicas [12, 14], but these studies have mostly dealt with open surfaces, and with complex texturing [15], while there is a lack of knowledge about the evaluation of the performance of high-aspect-ratio closed surface replicas. Walter et al. studied the replication of Narayanasamy and Radhakrishnan evaluated the replicas of small bores with a hole diameter in the range 1-3 mm and a maximum aspect ratio of 4, obtained by drilling, boring, reaming and honing [16].

The aim of the present paper is to evaluate the fidelity of through-hole replication for the measurements of area surface roughness and morphology of deep small holes, with aspect ratio between 12.5 and 25, which require a strong elongation of the replica during its extraction. These values are much greater than those reported in literature, between 8 and 8.8, for holes manufactured by short impulse laser and used in the advanced semiconductor industry [17,18].

Practical implementation consists in a non-destructive time-saving approach for product quality control in the field of micromachining. Industrial applications of the considered technique range from aerospace, to electronic and computers, with special relevance whenever small deep holes are required in super alloys: injection nozzles and cooling channels in turbine blades are two remarkable examples.

2 Experimental plan

Electro-drilling tests were performed on Inconel 718, using two pure copper (99.9 % Cu) electrodes: 0.4 mm diameter single channel and 0.8 mm diameter multi-channel (Fig. 1). The holes had aspect ratios of 25 and 12.5, respectively. The experiments were conducted using a Sodick K1C, a high-speed small-hole driller. Fresh VITOL-KS, a water-soluble commercial dielectric fluid, was pumped through the inner cavity of the electrodes: the dielectric flow was Q=25 g/min in the case of the 0.4 mm electrodes and Q=96 g/min when 0.8 mm electrodes were used.

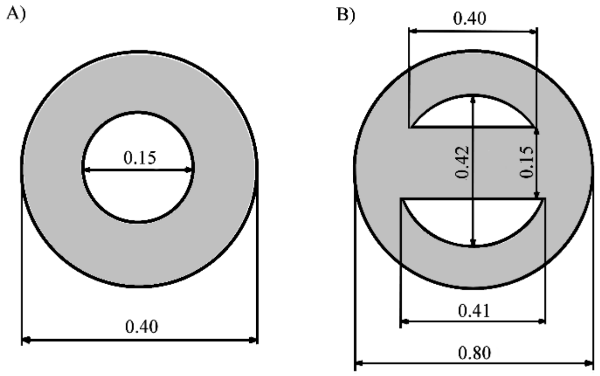

***Fig. 1** A) d=0.4 mm single channel electrode; B) d=0.8 mm multi-channel electrode.*

The electrical conductivity of the solution was measured at fixed intervals during the tests in a standard thermostated cell, with a Model 120 micro-processor conductivity meter. The cell constant was determined by measuring the conductivity of known solutions. The resistivity of the dielectric remained steady over the 1.00–1.15×10^3 Ωm range. The tests were performed in a temperature-controlled room to ensure thermal stability of the machine structure and a constant dielectric conductivity.

The EDD machine allows four input parameters, that is the peak current (I_p), pulse-on time (t_{on}), pulse-off time (t_{off}) and servovoltage, to be varied.

The drillings were performed using the process parameters shown in Table 1; the workpiece geometry is reported in Figure 2.

***Tab. 1** Process parameter values considered in the tests*

t_{on} [μs]	t_{off} [μs]	I_p [A]
6	14	53
10	30	13
12	28	3
		39
14		19
18		33
		53
20	20	19
		53
24	10	33
	14	39
26	12	39
28	4	13
	22	35
30		19
	8	15
		33
	6	19

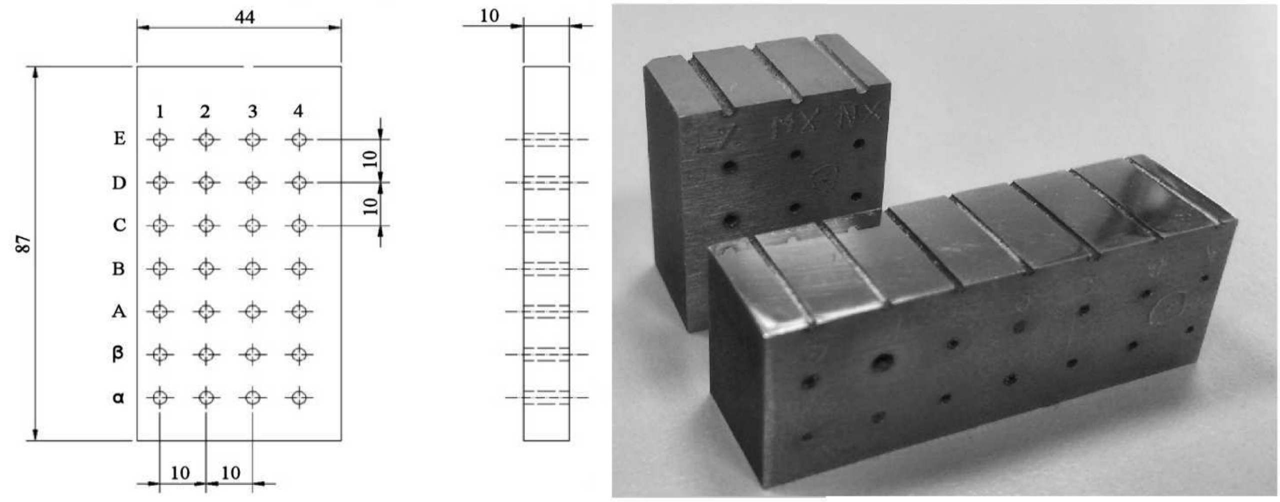

Fig. 2 *Workpiece geometry and performed drillings.*

The hole replicas were obtained both through the hole and on the hole cross section, by means of two different procedures:

The STC SHAPE-IN injection method. This method consists in pouring bicomponent silicone material (polyvinyl siloxane), at room temperature. After curing (about 50 min, room temperature), a silicone rubber replica, which has high elasticity, is obtained, and this elasticity allows it to be extracted from the unsectioned hole. It is important to ensure that the silicone material completely fills the hole: to this purpose, the injection is continued until the silicone material exits from the opposite side. As a consequence, a head is obtained at both sides of through-replicas, as shown in Figure 3c.

Application of the silicon material onto the sectioned hole. In order to directly measure the roughness of the hole on the electro-drilled surface, the specimens were sectioned with a micro-cutter along a plane containing the axis of the holes. The holes were filled with removable material, before cutting, in order to preserve the inner surface.

Unlike the work of other authors, no release agent was used in either procedure [12].

The following features were measured:

- Roughness of the sectioned holes (Figure 3a);
- Roughness of the sectioned hole replicas (Figure 3b);
- Roughness of the through-hole replicas (Figure 3c).

The roughness was measured in accordance with DIN EN ISO 4287/4288 and DIN EN ISO 25178.

A Nikon LV 150 Confovis Microscope instrument was used to assess the surface topography with:

- a 20X microscopic objective;
- 0.595 μm lateral resolution, 10 nm vertical quantisation and automatic field stitching;
- a scanned area of 0.5 x 4 mm^2 for the 0.8 mm diameter holes and a scanned area of 0.28 x 4 mm^2 for the 0.4 mm diameter holes.

The measurement region is shown in Figure 3.

Form removal, a FALS filter (according to ISO 16610-62) with a cut off of 0.08 mm for 0.08 μm, and bilateral symmetric threshold filtering (for the removal of spikes) were applied to the maps.

The 3D surface roughness average (S_a) was calculated on the maps. Surface homogeneity had been checked in advance to validate the operation. S_a provides a comprehensive measurement of the surface morphology.

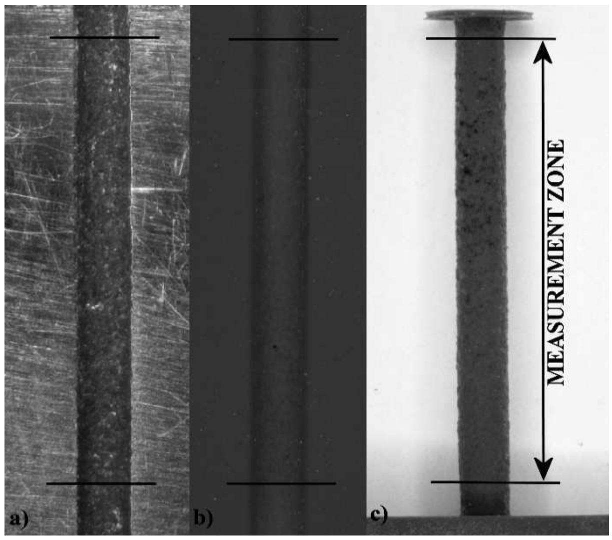

Fig. 3 *a) Sectioned hole; b) sectioned-hole replica; c) through-hole replica*

The comparison of the roughness values of the sectioned hole and those of the through-hole replicas allows the performances of the investigated solution (effectiveness of the process) to be evaluated.

The comparison of the roughness values measured on the two types of replicas allows the geometrical error introduced by the injection/extraction method (robustness of the process) to be estimated.

The fidelity of the sectioned hole replicas had previously been measured by comparing their roughness with that of the respective sectioned holes. Replicas often showed small dark contamination marks, due to the gluey effect of silicone on the debris and on the remelted layer produced during the electro-discharge process. Some authors have reported that, before replication, they degreased the specimens with a solvent in an ultrasonic cleaner and then rinsed them with alcohol for example [15].

In order to evaluate whether the described contamination affects the roughness measurement, a hole was cleaned and the replication process was repeated until the contamination was no longer observed. The roughness of the uncleaned and cleaned replicas was then measured and the two cases were compared (repeatability of the process).

3 Results and Discussion

As expected, and in accordance with literature data, on both of the used electrodes a linear correlation with high R-squared emerged between the sectioned hole roughness and that of the open replica (Figure 4).

When the replica was repeated on the same hole, in order to clean the machined surface, no significant differences between the first "dirty" replica and the last "clean" one were observed. The measuring of the roughness on the replica, obtained directly on the sectioned surface of a hole, is a process that offers good repeatability.

All the through-hole replicas of the d=0.8 mm holes could be extracted without any visible damage, while about 50 % of the through replicas of the d=0.4 mm holes showed rupture. A comparison between the roughness of the two replicas (through-hole and sectioned-hole) is available in Figure 5. The results pointed out that the process caused a sensible error for the smaller diameter hole, even when the replicas seemed intact. For the d=0.4 mm diameter the results show wide scattering and no correlation can be noticed (Figure 5A). In this case, attempts to determine a correlation, either linear or of higher order, turned into extremely low values of statistical significance. For the d=0.8 mm diameter, instead, a good linear correlation can still be found (Figure 5B). The replication of through holes, by means of injection and extraction, is found below its lower applicability limit in the case of the smaller holes considered in this study.

Figure 6 confirms that, for the d=0.8 mm diameter, there is a linear correlation with high R-squared between the roughness values measured on the sectioned holes and those obtained on the through-hole replicas. The fidelity of through replicas, instead, is lost for holes with d=0.4 mm diameter. As for Figure 5A, also for the data in Figure 6A it was impossible to find a satisfactory correlation. This is an important result, due to the fact that there are no alternative non-destructive technologies available for the evaluation of the surface morphology of these small and deep holes.

With respect to previous literature attainments [16], the current results show that the operative range of this technology may be extended down to 80% of the previous diameter limit and up to a three times higher aspect ratio.

A more detailed picture of the observed surface morphologies is available in Figures 7 and 8, where the 3 confocal maps of the same holes (d=0.4 mm in Fig. 7, d=0.8 mm in Fig. 8) are compared. It is very clear that, for the smallest holes, the replica extracted from the through-hole lacks copying accuracy.

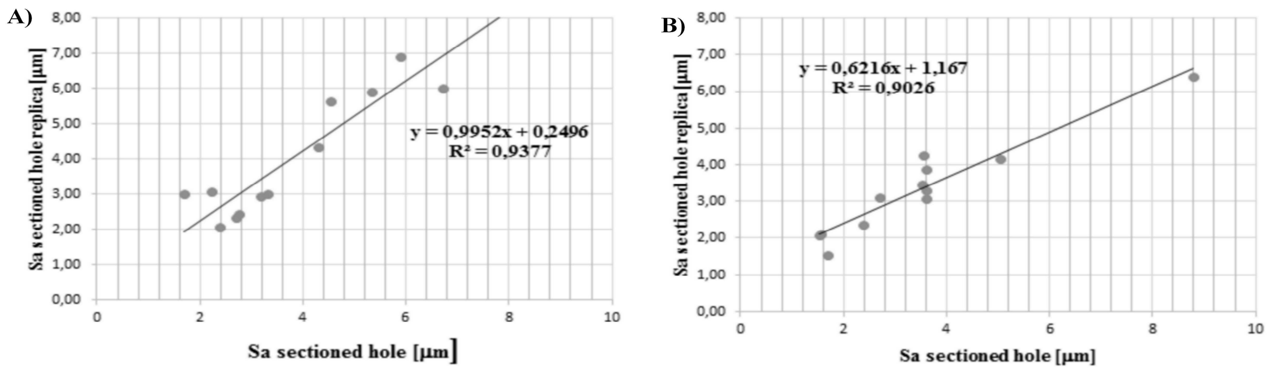

Fig. 4 *S_a of sectioned-hole replicas VS S_a of sectioned holes: A) d=0.4 mm electrode; B) d=0.8 mm electrode. A linear correlation can be observed between the sectioned hole roughness and that of the open replica for both of the considered diameters*

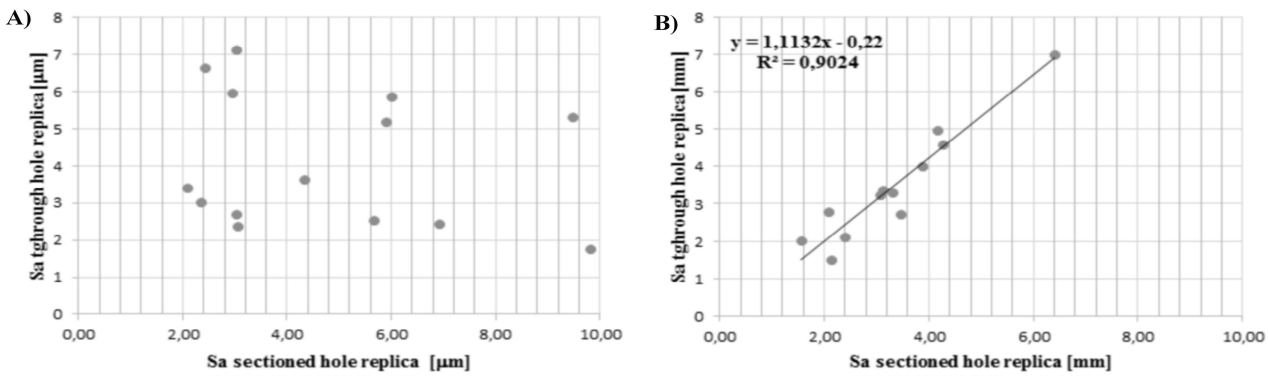

Fig. 5 *S_a of through-hole replicas VS S_a of sectioned-hole replicas: A) d=0.4 mm electrode; B) d=0.8 mm electrode.*

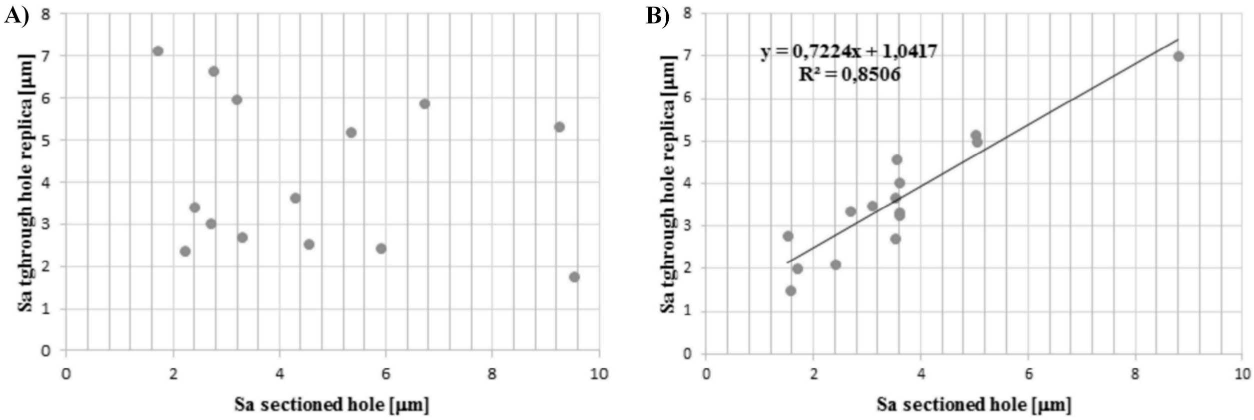

Fig. 6 *S_a of through-hole replicas VS S_a of sectioned holes: A) d=0.4 mm electrode; B) d=0.8 mm electrode.*

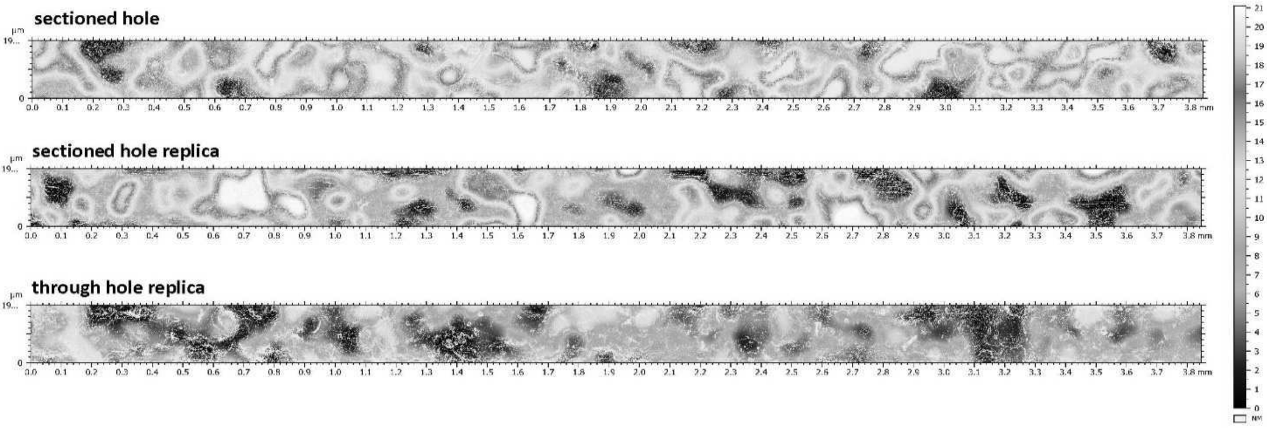

Fig. 7 *Comparison of the maps for a 0.4 mm hole (t_{on}= 20 µs t_{off}= 20 µs Ip=35 A)*

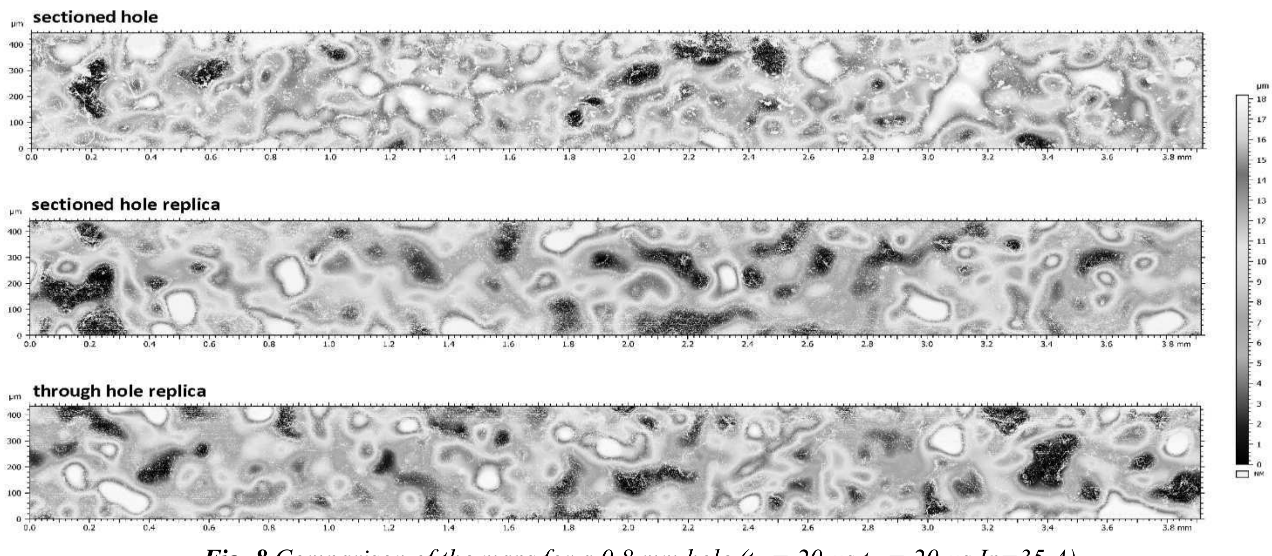

Fig. 8 *Comparison of the maps for a 0.8 mm hole (t_{on}= 20 µs t_{off}= 20 µs Ip=35 A)*

4 Conclusion

- Replicas of the sectioned holes are confirmed as a reliable repeatable tool for reproducing the surface morphology and measuring the surface roughness of small deep holes, down to 0.4 mm diameter with an aspect ratio as high as 25.
- Through-hole replicas, by means of injection and extraction of a silicone, can be successfully obtained for d=0.8 mm diameter holes with an aspect ratio of 12.5. The roughness measured on these replicas can be reliably used to predict that of the sectioned hole replicas and of the sectioned holes themselves. The replication process does not introduce any significant shape or morphology errors.
- For the holes with 0.4 mm diameter and aspect ratio of 25, the injection/extraction replication process is below the limit of reliable application.

- An extension of the operative range of through-hole replicas, as a method for the measurement of micro-machined holes, is proven viable up to an aspect ratio more than three times higher and a diameter almost 80% lower than the limits previously set in literature.

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