Journal of Mechanical Science and Technology

Investigation on power discharge in micro-EDM stainless steel drilling using different electrodes

--Manuscript Draft--

Manuscript Number:	
Full Title:	Investigation on power discharge in micro-EDM stainless steel drilling using different electrodes
Article Type:	Original Paper
Keywords:	micro-EDM; micro-Drilling; Tool Wear Ratio; Material Removal Rate; Process Performance.
Corresponding Author:	Gianluca D'Urso ITALY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	
Corresponding Author's Secondary Institution:	
First Author:	Gianluca D'Urso
First Author Secondary Information:	
Order of Authors:	Gianluca D'Urso
	Chiara Ravasio, Dr.
	Giancarlo Maccarini, Prof.
Order of Authors Secondary Information:	
Abstract:	The present work deals with the execution of through micro-holes on stainless steel plates using a micro-EDM (Electrical Discharge Machining) machine. The investigation focuses on the influence of different electrodes' materials and power discharge on both the process performance and the dimensional characteristics of the holes. The experimental campaign was carried out by varying peak current and voltage in order to achieve both high and low power discharge conditions. Tubular electrodes made of two different materials (tungsten carbide and brass) were used. The indexes taken into account were Material Removal Rate (MRR), Tool Wear Ratio (TWR), Diametral overcut (DOC) and Taper Rate (TR). Brass electrode always resulted to be the best solution in terms of drilling speed even though the wear of this electrode type is remarkable higher than the tungsten one. On the opposite, tungsten carbide electrodes resulted to be the best solution when high dimensional and geometrical precision is required. Concerning the finishing of the hole inner surface, the best results were achieved using tungsten carbide electrode.
Suggested Reviewers:	Samuel Bigot, Dr. Cardiff University - UK BigotS@cardiff.ac.uk
	Irene Fassi, Dr. National Research Council - Italy irene.fassi@itia.cnr.it
	Elisabetta Ceretti, Prof. University of Brescia – Italy elisabetta.ceretti@unibs.it
	Stefan Dimov, Prof. University of Birmingham - School of Mechanical Engineering s.s.dimov@bham.ac.uk

Investigation on power discharge in micro-EDM stainless steel drilling using different electrodes

G. D'Urso[1], G. Maccarini[2], C. Ravasio[3]

[1] University of Bergamo – DIGIP – Viale Marconi 5, 24044 Dalmine (BG) - Italy – durso@unibg.it

[2] University of Bergamo – DIGIP – Viale Marconi 5, 24044 Dalmine (BG) - Italy – giancarlo.maccarini@unibg.it

[3] University of Bergamo – DIGIP – Viale Marconi 5, 24044 Dalmine (BG) - Italy – chiara.ravasio@unibg.it

Keywords: micro-EDM, micro-Drilling, Tool Wear Ratio, Material Removal Rate, Process Performance

Abstract

The present work deals with the execution of through micro-holes on stainless steel plates using a micro-EDM (Electrical Discharge Machining) machine. The investigation focuses on the influence of different electrodes' materials and power discharge on both the process performance and the dimensional characteristics of the holes. The experimental campaign was carried out by varying peak current and voltage in order to achieve both high and low power discharge conditions. Tubular electrodes made of two different materials (tungsten carbide and brass) were used. The indexes taken into account were Material Removal Rate (MRR), Tool Wear Ratio (TWR), Diametral overcut (DOC) and Taper Rate (TR).

Brass electrode always resulted to be the best solution in terms of drilling speed even though the wear of this electrode type is remarkable higher than the tungsten one. On the opposite, tungsten carbide electrodes resulted to be the best solution when high dimensional and geometrical precision is required. Concerning the finishing of the hole inner surface, the best results were achieved using tungsten carbide electrode.

1. Introduction

In recent years, the trends in manufacturing technology often deals with the miniaturization of products and components and the need for products containing micro-features has shown a pronounced and steady growth in several fields of application. Also the need for products containing micro-holes has shown remarkable growth [1-2]. Micro holes are widely used for the production of several industrial components such as medical and optical devices, turbine blades cooling channels, diesel fuel injection nozzles. Many technologies based on mechanical, electro-physical or chemical processes can be used to obtain micro holes, for example: ultrasonic vibration machining, mechanical drilling using micro-tips, laser beam drilling, electro-chemical machining and electrical discharge machining. Each process has its advantages and limitations related to the field of application, the material to be machined, the accuracy and the process performance required [3].

Micro EDM (Electrical Discharge Machining) is considered one of the most important technologies in micro-drilling, in particular, micro-EDM is effective in drilling very small and very high aspect ratio burr-free micro-holes. Since micro EDM is a contact-less process, it is possible to fabricate micro parts and micro-scale features without distortion or brakeage due to physical forces [4]. Moreover, this technology can be applied on every conductive materials independently by the mechanical properties. In this process the material is removed through a controlled erosion due to a series of electric sparks between the tool and the workpiece. The material is melted and vaporized because of the high temperature generated by the electrical discharges. Because of the high temperature caused by the sparks, the electrode material is also melted and vaporized, giving rise to a remarkable electrode wear. The EDM process is basically a thermal process and it is regulated through the control of several process parameters such as voltage, current, pulse duration, sparking gap, frequency and others. In EDM drilling, these parameters have a no negligible effect on both erosion process (wear ratio, material removal rate) and machined workpiece (dimensional and geometrical accuracy, surface finishing). Not only process parameters can affect the final output but also the tool and the workpiece material properties. Beyond a certain value of the aspect ratio of micro hole, abnormal discharges occur more frequently, resulting in machining speed reduction, or in geometrical and dimensional alteration of the holes. These phenomena can be due to the debris accumulation at the bottom of the hole that causes the abnormal discharges when the hole is drilled deeply [5].

Concerning the process performance, the use of the proper process parameters is essential to achieve high material removal rate. For example, micro electro discharge drilling of a titanium super alloy was investigated in [6], showing that machining performance is mostly affected by peak current and pulse on time. Small deep hole drilling of Inconel 718, using EDM technology with a pure electrolytic copper electrode, was carried out in [7] varying peak current, pulse on time, duty factor and electrode speed. The results revealed that MRR is more influenced by peak current, duty factor and electrode rotation, whereas depth average surface roughness is strongly influenced by peak current and pulse on time.

In micro-EDM drilling, the tool wear can be considered a more important issue than for conventional drilling and many studies have been carried on for the optimization of micro-drilling process by adequate experiments [8]. As regards the electrode, both geometry and material have an influence on MRR and electrode wear. In [9] it has been demonstrated that the single-channel electrode provides better material removal rates and lower electrode wear ratios than multi-channel tubular electrode. However multi-channel electrodes produce better surfaces and lower hardness values than single-channel electrodes. An investigation on the electrode wear behavior of tube and bar electrodes was carried out in [10]; the electrode wear variation under different operating condition and a method for calculating volumetric wear ratio is proposed.

Concerning the tool material used for the electrodes, the experiments described in [11] demonstrates that, for titanium alloy workpiece, brass and copper electrodes permit to obtain the minimum machining time while machining time increases a lot using special carbide electrodes; on the contrary, minimization of tool wear ratio can be obtained using special carbide electrodes with respect to copper and brass.

The dimensional and geometrical aspects of the micro holes are often resumed by two different indicators. The first one is the Diametrical Overcut (DOC): this indicator gives information on the variation between the effective top diameter and the nominal electrode diameter, which is usually influenced by the sparking gap due to the process parameters.

The overcut significantly affects the spark hole dimensional accuracy and becomes important for high component tolerance requirements. Several studies have shown that the overcut is associated with many variables, including electrical discharging parameters, such as discharge voltage, current, duty cycle, and pulse duration [12]. The second indicator is the Taper Rate (TR), which gives information about the tapering of the holes. Generally the holes result with the top diameter larger than the bottom diameter, but in other cases [13] it was observed an undesired inverse-taper of hole shape coming from the discharge between processing debris and lateral wall of holes. Basing on this considerations, it is possible to assert that the optimized conditions and process parameters for micro-drilling has often be determined only by experiments, because of the unhelpfulness of the conventional drilling standard process parameters and the lack of suitable manufacturers parameter data [14]. Thus, the real effects of micro-EDM process parameters, electrodes and workpiece materials on the final output are partially unknown and have yet to be clarified.

The present paper is aimed at the evaluation of the influence of different electrode materials and power discharge on both process performance and dimensional characteristics of micro holes on stainless steel plates. The experimental campaign was carried out by varying peak current and voltage in order to achieve both high and low power discharge condition. Tubular electrodes made of two different materials (tungsten carbide and brass) were used.

2. Experimental set up

The micro EDM machine used in the experimental campaign was a Sarix SX-200. A detail is reported in Fig. 1. The micro holes were executed on stainless steel plates (AISI 304) having a thickness equal to 3 mm. Two electrodes' materials, brass and tungsten carbide, having different thermal, physical and electric characteristics, were used (Table

1). Both electrodes are tubular, with an outer diameter equal to 0.3 mm and an inner diameter equal to 0.12 mm.

Considering that the discharge energy can be calculated as given in Eq. (1), during the experimental campaign, peak current (I) and voltage (V) were varied in order to study their effect on process performance and on the output in terms of geometrical characteristics.

$$E = \int_0^{t_{on}} I(t) \cdot V(t) \cdot dt \quad [\mathrm{J}] \qquad (1)$$

Finally, hydrocarbon oil was used as dielectric with an internal washing pressure equal to 6 bar.

The process parameters kept fixed, as a function of the electrode used, are reported in Table 2 while peak current and voltage were varied basing on a Design of Experiments (DOE) with two levels, central point and five repetition (Table 3). It can be noted that the fixed parameters and the ranges of the variable ones differ for the two electrode materials; this solution was used in order to test suitable technological windows for both materials. The execution order of the experiments was randomized to avoid possible systematical errors. The combination of the variable parameters resulted into 9 different technologies and in a total amount of 45 micro holes for each electrode (Table 3).

A program for the automatic execution of the holes using the different technologies was implemented into the Sarix EDM machine. This program permits to record the machining time and the frontal electrode wear for each micro hole. At the end of each hole, the electrode clamp was moved to a specific reference point in order to measure the electrode wear by an electrode touching operation. The frontal tool wear (TW) was calculated as difference between the initial and the final length of the electrode. At the end of each hole drilling, the electrode tip was cut using the wire EDM unit to restore the same initial conditions for all the tests.

3. Evaluation of the process performance and the geometrical characteristics of micro holes

The evaluation of the process performance using two different electrodes was conducted considering the drilling time expressed in [s] and the TWR (Tool Wear Ratio) calculated as given in Eq. 2.

$$TWR = \frac{V_{tool}}{V_{workpiece}} \tag{2}$$

where V_{tool} is the volume of the material removed from the electrode and the $V_{workpiece}$ is the volume of the material removed from the workpiece. The typical EDM micro hole has a cone-shaped geometry with the top diameter larger than the bottom diameter. In order to calculate the volume of material removed from the workpiece, the diameters were measured at both the top and the bottom of each hole through an optical measuring microscope at a magnification of 100X. $V_{workpiece}$ was calculated as the volume of a frustum of cone (see Eq. 3) where D_{top} and D_{bottom} are respectively the top and the bottom diameter of the micro hole and h is the thickness of the plate.

$$V_{workpiece} = \frac{\pi h(D_{top}^2 + D_{top}D_{bottom} + D_{bottom}^2)}{12} \tag{3}$$

The volume of the material removed from the tool is calculated as the volume of the tube having diameters equal to the nominal electrode outer and inner diameters (respectively D_{ext} and D_{int}) and height equal to the measured wear (h_t), as reported in Eq. 4:

$$V_{tool} = \frac{\pi h_t(D_{ext}^2 - D_{\text{int}}^2)}{4} \tag{4}$$

The geometrical characteristics of micro holes were evaluated considering Diametral Overcut (DOC) and Taper Rate (TR) calculated as follows:

$$DOC = 100\frac{D_{top} - D_{ext}}{D_{ext}} \tag{5}$$

$$TR = \frac{D_{top} - D_{bottom}}{h} \quad (6)$$

4 Analysis of the results

The experimental campaign was conducted varying two important electrical process parameters (peak current and voltage) and the analysis of the results aims at pointing out the effects of the power discharge on both the process performance and the geometrical characteristics of micro holes. The nominal power discharge can be calculated as the product between nominal value of peak current [index] and voltage [V]. The following analysis reports the average of the values of the five repetitions for each tested conditions.

4.1 Process evaluation using tungsten carbide electrode

Fig. 2 shows the drilling time and the geometrical characteristics of micro holes, in terms of top and bottom diameter, obtained using tungsten carbide electrode as a function of the nominal power discharge. The time linearly decreases for increasing values of the power discharge; the top and the bottom diameter are well fitted by a parabolic curve. The correlation indexes are in any case satisfactory. Increasing power discharge, the amplitude of the electric sparks is larger, causing a reduction in drilling time and an increase in the hole top diameter.

Fig. 3 shows the drilling time and the TWR as a function of the power discharge, obtained using tungsten carbide electrode. TWR shows a linear dependence on power discharge with an opposite behavior with respect to the drilling time. It is interesting to observe how a reduction of about 50% in drilling time results in increasing TWR of about 20%.

Fig. 4 shows DOC and TR of micro holes as a function of the power discharge, using tungsten carbide electrode. Both the indicators follow a parabolic curve as a function of power discharge; in fact the top diameter, and consequently DOC, is larger when the electrical process parameters are “more aggressive”. The bottom diameter variation range is smaller than the top one (Fig. 2); this explains that increasing the power discharge, the taper rate of micro holes increases too. The evacuation of debris produced during the drilling process causes the parasite discharges on the lateral side of micro holes; increasing the power discharge, the effect of these parasite sparks results to be amplified.

4.2 Process evaluation using brass electrode

Fig. 5 shows the drilling time and the geometrical characteristics of micro holes, in terms of top and bottom diameter, obtained using brass electrode as a function of the power discharge. While time and bottom diameter decrease increasing the power discharge, following a parabolic and a linear law respectively, no fitting law with a significant regression coefficient value was found for the top diameter. In this last case, in effect, a large data scatter was observed.

A trend in the bottom diameter data was found even if the difference between maximum and minimum value is only few micrometers.

In Fig. 6, drilling time and TWR as a function of the power discharge, obtained using brass electrode, is reported. In this case too, TWR curve shows a linear trend, increasing when the power discharge increases. In this case a reduction of about 30% in drilling time results in increasing TWR of the same percent value.

The scatter observed for the top diameter affects DOC and TR curves; therefore no fitting laws with a significant correlation coefficient were found for these indexes (Fig. 7).

4.3 Comparison between tungsten carbide and brass electrodes

In order to compare the performance of tungsten carbide and brass electrodes, two process conditions were taken into account: low and high discharge energy. Brass electrode, having a higher electrical conductivity and lower melting temperature, permits to obtain micro holes faster even though with negative effects on the tool wear (Figs. 8-9). A remarkable difference in terms of time and TWR can be observed between the two materials.

Regarding the geometrical characteristics of micro holes, the manufacturing process is more accurate when tungsten carbide electrode is used: the diameters, top and bottom, DOC and TR are lower using tungsten carbide electrode instead of brass one (Figs. 10-12).

Top view, internal surface and roughness surface profile of micro holes are reported in Fig. 13. The images refer to holes obtained using both the electrode types and two different process conditions (low and high energy). In general, high energy results in larger top diameter and dimension of the craters in the inner surface. Using brass electrode, the top view of micro holes results more affected by solidification of melted material. This phenomenon can be related to the higher electrical conductivity of the brass and to the higher power discharge required; at the same time, the re-solidified material on the top of the surfaces cause a more difficult optical measurement of the diameters.

As a general remark, brass electrode always represents the best solution in terms of drilling speed. Even though the wear of brass electrode is remarkable higher than tungsten one (TWR increases from 50 to 100%), the lower cost of electrode tools can justify this choice for several conditions. On the opposite, tungsten carbide electrodes represent the best solution when high dimensional and geometrical precision is required. Finally, using tungsten carbide electrode the level of energy affects the roughness of the internal surface of micro holes: low energy permits to obtain a better surface finishing. This result is not true for brass electrode where the level of energy slightly affects the internal surface finishing.

5. Conclusive remarks

The influence of electrode material and power discharge in micro-EDM stainless steel drilling on the process performance (drilling time and TWR) and on the geometrical characteristics (overcut and taper rate) of micro holes was investigated. Power discharge was varied acting on peak current and voltage and the following conclusion can be drawn:

- using tungsten carbide electrode, an increase in power discharge is reflected on a reduction in drilling time, damaging TWR and overcut. In fact, the amplitude of the electric sparks is larger, the top diameter increases and therefore taper rate increases too. Drilling time and TWR have a linear dependence on power discharge while overcut and TR follow a parabolic law;
- using brass electrode, time decreases increasing the power discharge while TWR increases, following a parabolic and a linear law respectively. A large data scatter was observed for the top diameter casing no fitting laws with a significant correlation coefficient for DOC and TR;

- the higher electrical conductivity of brass with respect to tungsten carbide permits to obtain micro holes faster; as negative effect, the lower melting temperature of brass than tungsten carbide electrode causes an increase in tool wear;
- the relation between drilling time and TWR is significantly affected by the electrode material; in particular this relation is more sensible for brass electrode;
- the manufacturing process is more accurate when tungsten carbide electrode is used: the diameters, top and bottom, DOC and TR are lower using tungsten carbide electrode instead of brass; moreover, using brass electrode, the top view of micro holes results more affected by solidification of melted material;
- in general using tungsten carbide electrode and low energy parameters it is possible to achieve a better surface finishing with respect to brass electrode.

As a general remark, the choice of electrode material has effects on the process performance in terms of drilling time and TWR, on the level of accuracy of micro hole and finally on the cost of the operation.

Reference

1. M. M. Sundaram, G. B. Pavalarajan and K. P. Rajurkar, A Study on Process Parameters of Ultrasonic Assisted Micro EDM Based on Taguchi Method, JMEPEG 17 (2008) 210–215.

[2] H. Weule et al., International state of the art of micro production technology, Production Engineering XI, 1 (2004), 29-36.

[3] L. Jianzhong, Y. Guoqiang, W. Cong, G. Xuejie and Y. Zuyuan, Prediction of aspect ratio of a micro hole drilled by EDM, Journal of Mechanical Science and Technology 27 (1) (2013) 185-190.

[4] S. M. Sona, H. S. Limb, A.S. Kumarb, M. Rahmanb, Influences of pulsed power condition on the machining properties in micro EDM, Journal of Materials Processing Technology 190 (2007) 73–76.

[5] A. A. Khan, Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes, The International Journal of Advanced Manufacturing Technology 39 (5) (2008).

[6] B. B. Pradhan, M. Masanta, B. R. Sarkar, B. Bhattacharyya, Investigation of electro-discharge micro-machining of titanium super alloy, International Journal Advanced Manufacturing Technology 41 (2009) 1094-1106.

[7] P. Kuppan, A. Rajadurai, S. Narayanan, Influence of EDM process parameters in deep hole drilling of Inconel 718, International Journal Advanced Manufacturing Technology 38 (2008) 74-84.

[8] B. Denkena, H. W. Hoffmeister, M. Reichstein, S. Illenseer, M. Hlavac, Micro-machining processes for microsystem technology, Microsyst Technol 12 (2006) 659–664.

[9] O. M. Yilmaz, A. Okka, Effect of single and multi-channel electrodes application on EDM fast hole drilling performance, International Journal Advanced Manufacturing Technology 51 (2010) 185-194.

[10] D. T. Pham, A. Ivanov, S. Bigot, K. Popov, S. Dimov, An investigation of tube and rod electrode wear in micro EDM drilling, Int J Adv Manuf Technol 33 (2007) 103–109.

[11] G. D'Urso, M. Longo, G. Maccarini, C. Ravasio, Electrical discharge machining of micro holes on titanium sheets, Proceedings of the 5th International Conference on Micro- and Nanosystems, ICONE14, Washington, DC, USA, August 28-31 (2011).

[12] T. Haoa, L. Yonga, Z. Longa, L. Baoquanb, Mechanism design and process control of micro EDM for drilling spray holes of diesel injector nozzles, Precision Engineering 37 (2013) 213– 221.

[13] H. N. Chiang, J. J. Junz Wang, An analysis of overcut variation and coupling effects of dimensional variable in EDM process, Int J Adv Manuf Technol 55 (2011) 935–943.

[14] H. W. Hoffmeister, S. Illenseer, Burr formation and reduction in micro drilling of metals, Prod Eng WGP 11, 1 (2004) 1–4.

Figure 12. TR using tungsten carbide and brass electrodes.

Figure 13. SEM images and roughness surface profiles of micro holes obtained using tungsten carbide and brass electrodes and two different process conditions.

Table 1. Physical properties of electrodes' material.

Physical Property	**Brass**	**Tungsten carbide**
Density [g/cm^3]	8.75	15
Melting range [°C]	1000	2850
Electrical resistivity [Ωcm]	$4.7*10^{-6}$	$65*10^{-6}$
Thermal conductivity [W/mK]	159	75
Specific heat [J/(g°C)]	0.38	0.215
Hardness Rockwell	66 (F)	90 (A)

*Source: www.matweb.com

Table 2. Fixed process parameters.

	Brass	Tungsten carbide
Energy	365	365
Polarity	-	-
Frequency [kHz]	130	110
Width [μs]	4	4.7
Gain	120	50
Gap [%]	50	70
Spindle rotational speed	100%	100%
Regulation	03-01	03-01

Table 3. Technologies defined by DOE.

Tool type	Brass		Tungsten Carbide	
	I [index]	V [V]	I [index]	V [V]
Tech.1	40	110	65	110
Tech.2	40	93	65	135
Tech.3	40	127	65	160
Tech.4	50	120	40	135
Tech.5	50	100	50	120
Tech.6	30	100	50	150
Tech.7	30	120	80	120
Tech.8	57	110	80	150
Tech.9	23	110	90	135

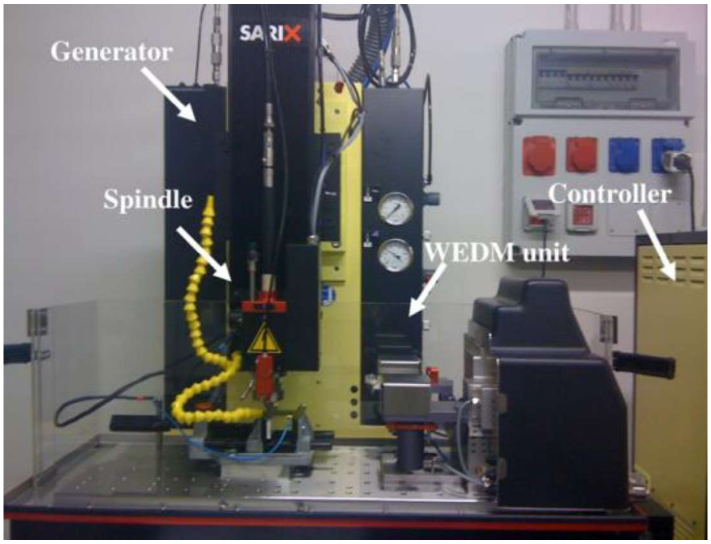


Figure 1. Sarix SX-200, details of the micro-EDM system.

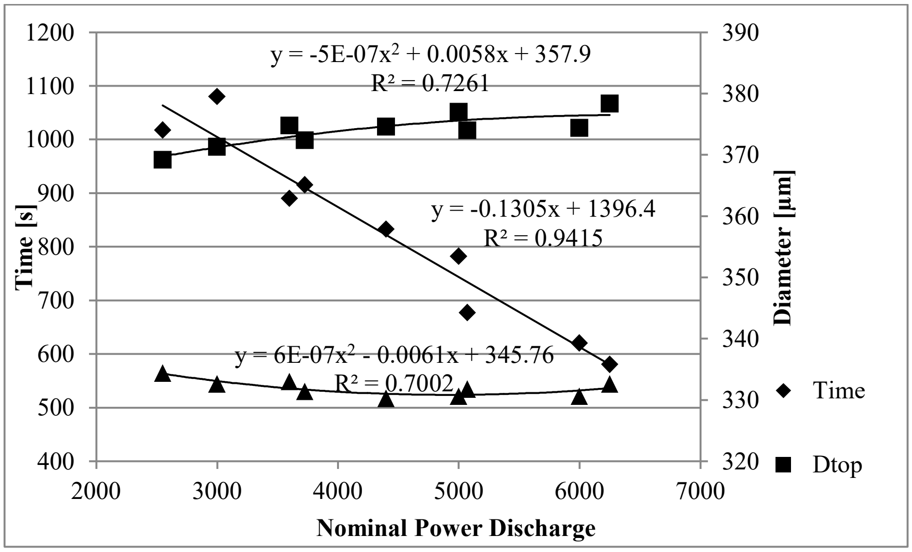


Figure 2. Drilling time and diameters of micro holes as a function of the power discharge, obtained using tungsten carbide electrode.

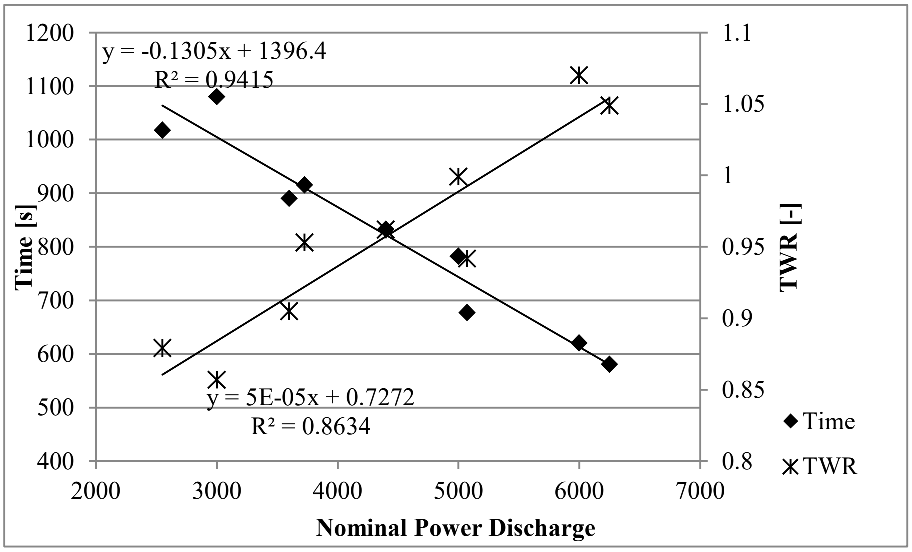


Figure 3. Drilling time and TWR as a function of the power discharge, obtained using tungsten carbide electrode.

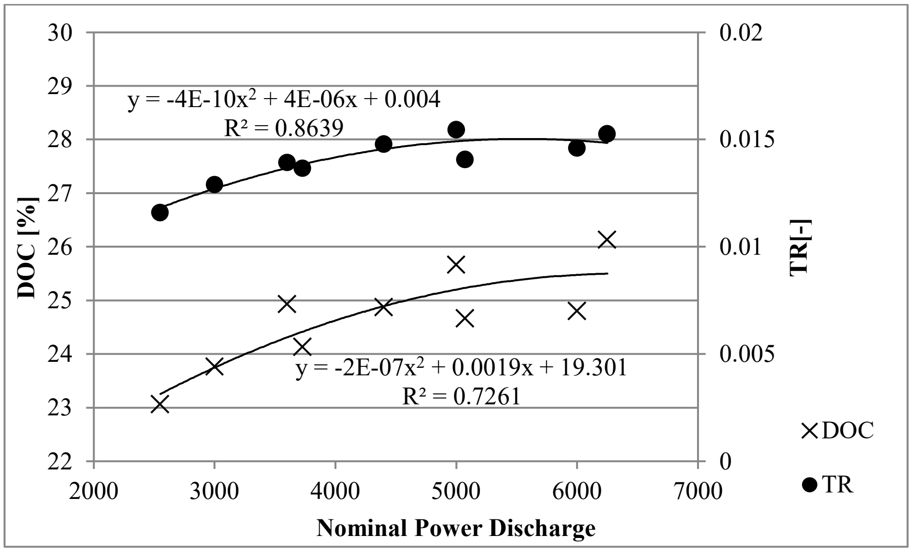


Figure 4. DOC and TR of micro holes as a function of the power discharge, using tungsten carbide electrode.

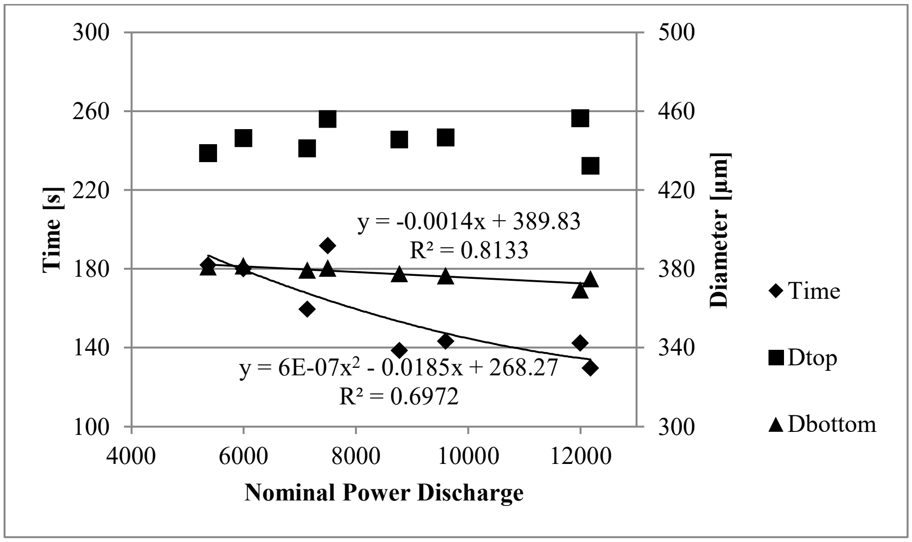


Figure 5. Drilling time and diameters of micro holes as a function of the power discharge, obtained using brass electrode.

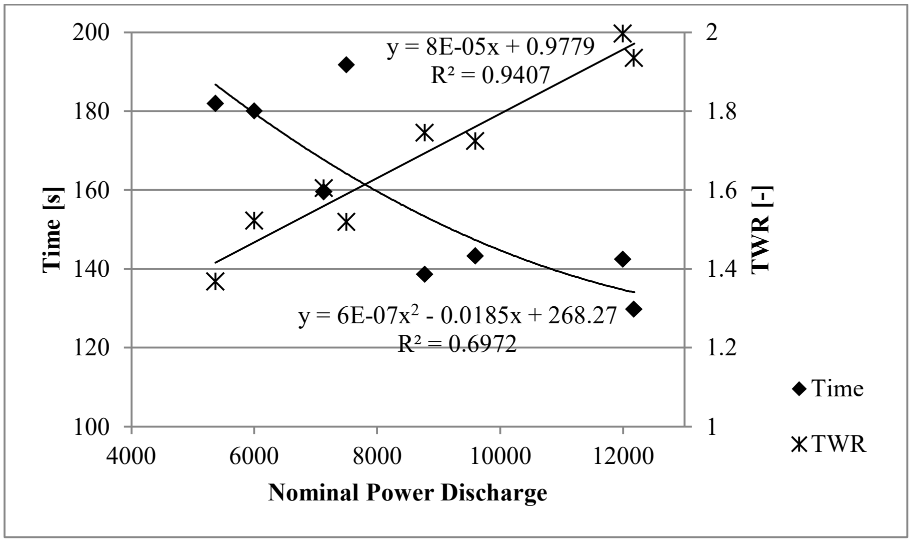


Figure 6. Drilling time and TWR as a function of the power discharge, obtained using brass electrode.

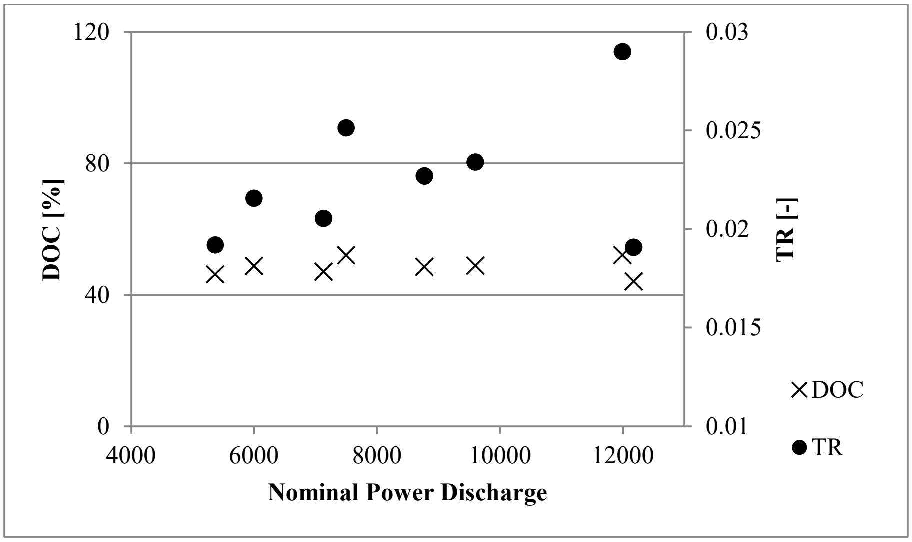


Figure 7. DOC and TR of micro holes as a function of the power discharge, using brass electrode.

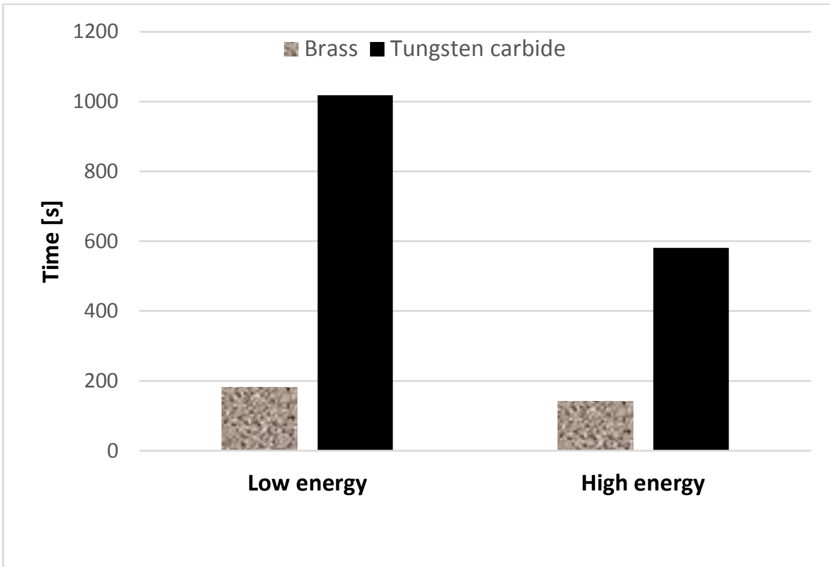


Figure 8. Drilling time using tungsten carbide and brass electrodes.

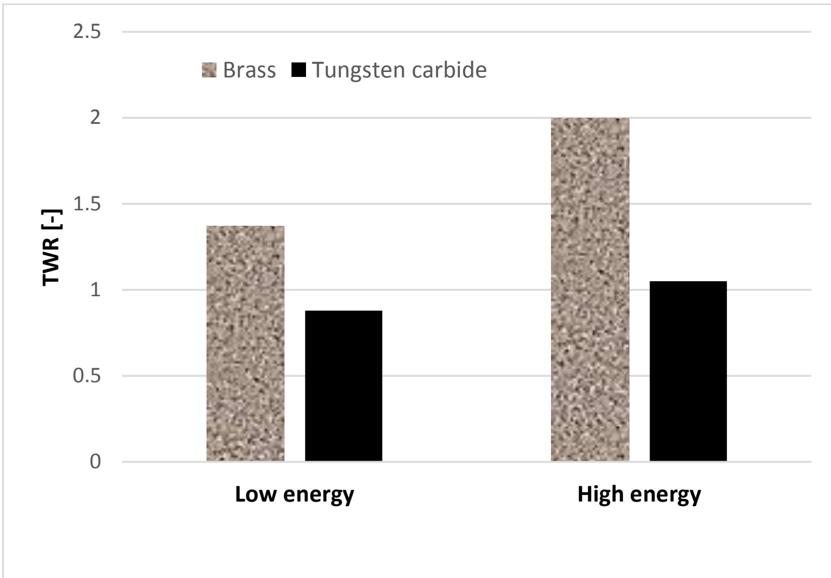


Figure 9. TWR using tungsten carbide and brass electrodes.

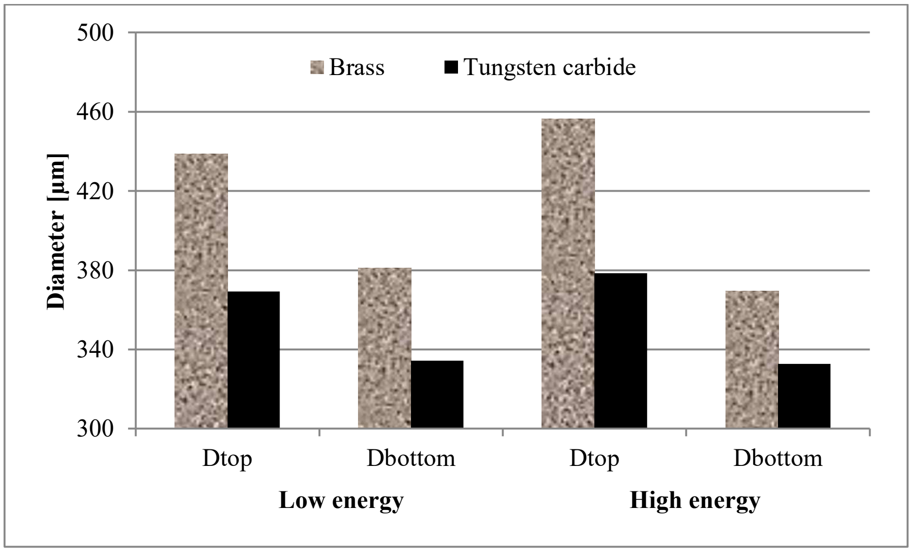


Figure 10. Top and bottom diameter of micro holes using tungsten carbide and brass electrodes.

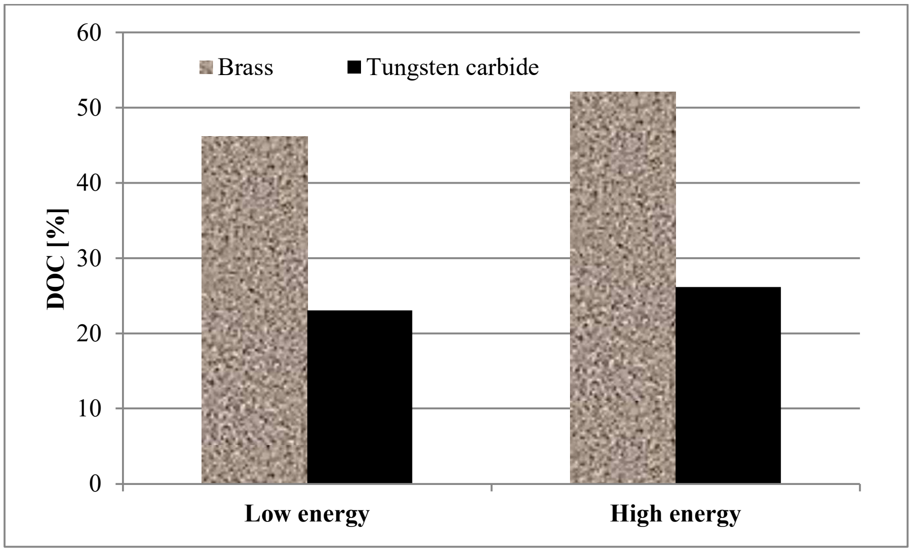


Figure 11. DOC using tungsten carbide and brass electrodes.

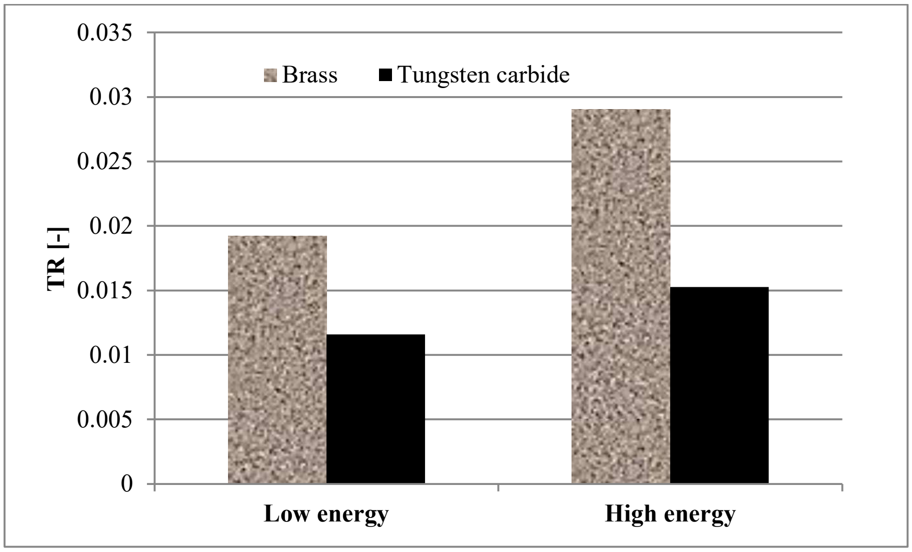
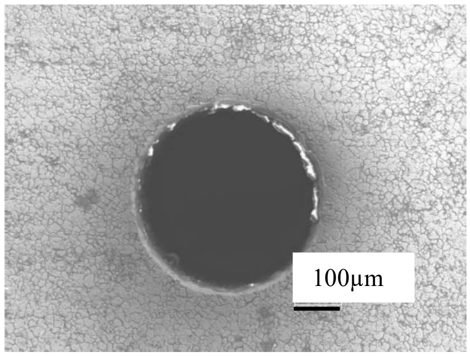
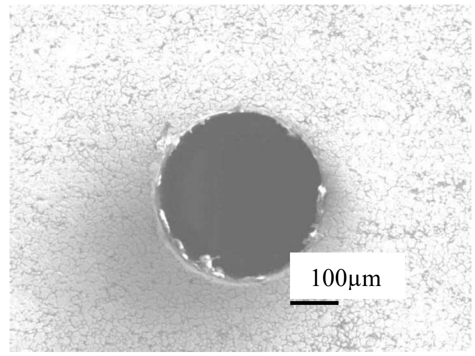
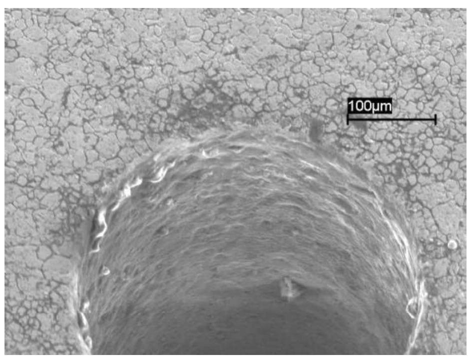
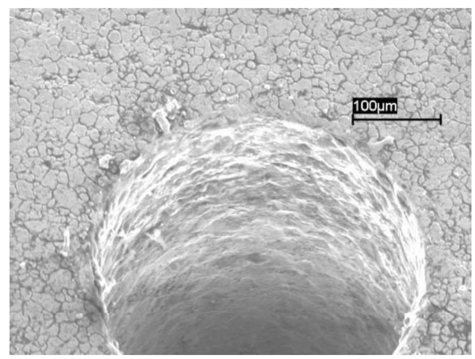
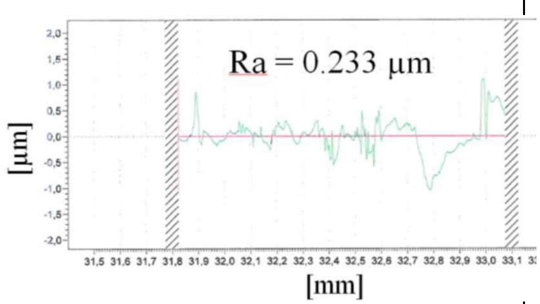
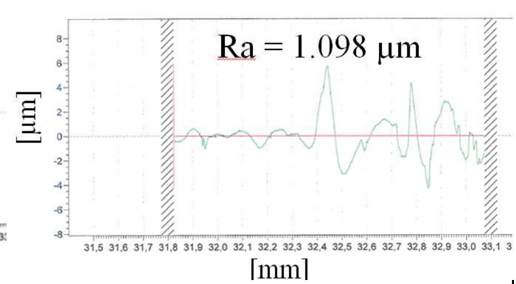


Figure 12. TR using tungsten carbide and brass electrodes.

<table>
<tr><td></td><td>Low Energy</td><td>High Energy</td></tr>
<tr><td rowspan="3">Tungsten Carbide</td><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

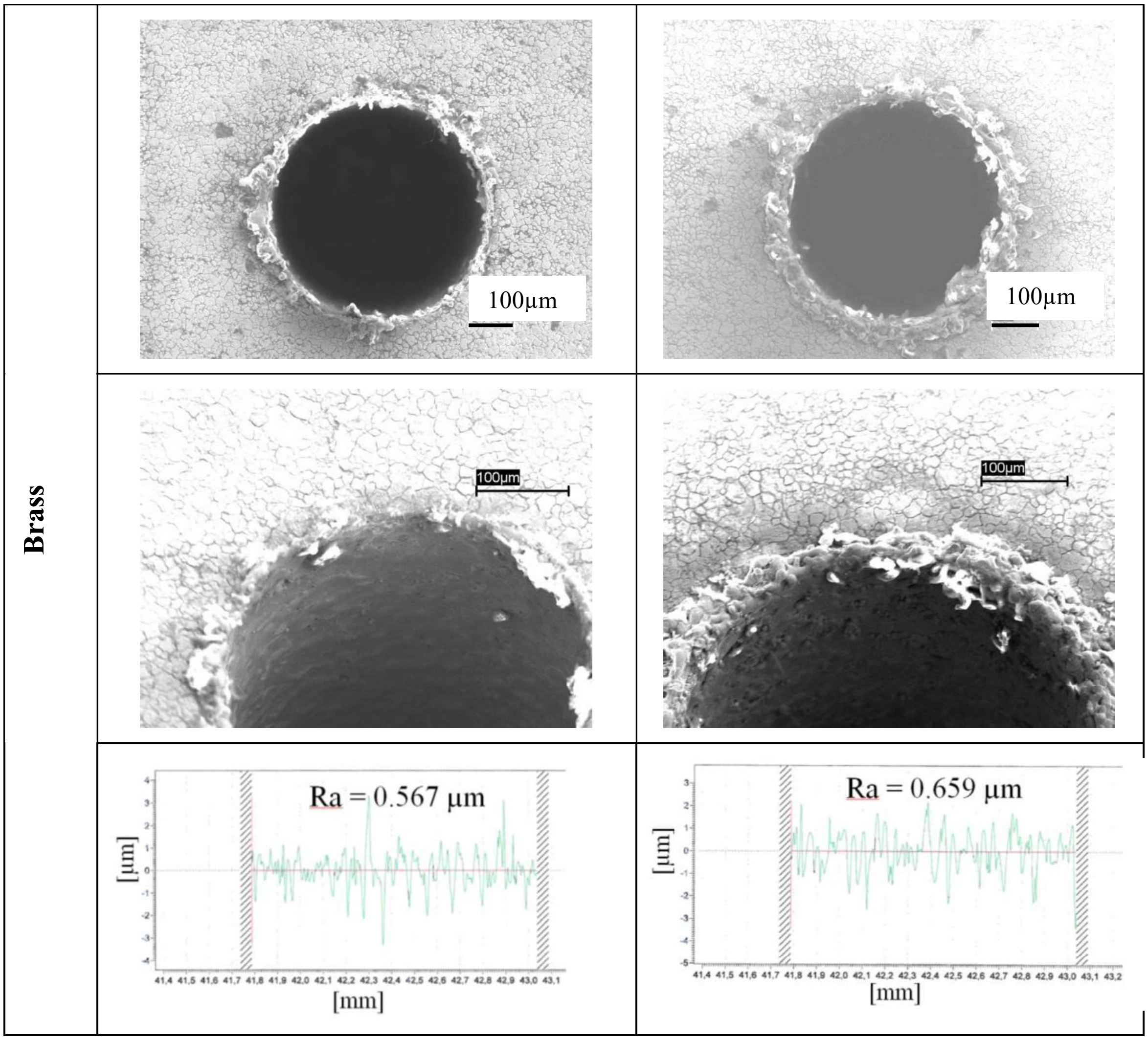


Figure 13. SEM images and roughness surface profiles of micro holes obtained using tungsten carbide and brass electrodes and two different process conditions.