

CHARACTERIZATION OF HOLES OBTAINED BY FAST HOLE EDM DRILLING AND TREPANNING LASER DRILLING IN INCONEL 718 PLATES

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Abstract Fast Hole Drilling EDM and Trepanning Laser Drilling are applied in turbine blades cooling holes manufacturing and repair. The purpose of the present work is to characterize the channel surface of the microholes machined by these different techniques in plates of a Inconel 718 Nickel superalloy. From this characterization, it is possible to verify which technique allows to obtain holes with greater control of surface roughness and to verify the characteristics of machined surface, as presence of craters and spatters caused by the method of machining used. EDM holes were drilled using a two-electrode material: copper and brass; and by Nd: YAG laser drilling by trepanation. A statistical design was defined to evaluate the influence of the main input parameters. It was verified that the roughness had significant variation with the different manufacturing techniques, as well as input parameters for each technique. Roughness in EDM holes was more influenced by the variation in the material of the electrode and current in the EDM and by the energy in the laser drilling. It was observed that the presence of spatters and craters in drilling by EDM is greater when compared to Trepanning Laser Drilling. Therefore, with regard to surface finishing, it is possible to define that the technique of Trepanning Laser Drilling has advantages over drilling by EDM of fast hole.

Palavras-chave: Trepanning Laser Drilling, EDM fast hole drilling, surface roughness, central composite statistical design, cooling microholes

1. INTRODUCTION

Fast Hole EDM Drilling and Trepanning Laser processes are key features in applications where it is necessary to produce small diameter holes (less than 1 mm). One of the most important examples of the use of these processes is the manufacturing of cooling holes in turbine components. Laser and EDM drilling methods are used for this purpose not only because they are able to produce small holes, but also owing to their ease of use automation.

The technique of laser drilling, by trepanation, is characterized by its ability to produce holes with greater dimensional control and less amount of spatter than Percussion Laser Drilling. In this technique a central through-hole is made using a pulsed Laser beam and then the Laser beam performs the radial movement until the final diameter and follows the trajectory of that diameter. In the process of fast hole EDM drilling, rotating electrodes are used with void core through which the dielectric fluid passes.

Ashkenasi et al. [1] and Jahns et al. [2] investigated the applicability of microhole by laser trepanation in industrial components, and, through an evaluation of the microhole geometry, were able to determine whether the industrial application of the process was feasible, given the quality in the dimensional control at the entrance and exit of the hole. D'Urso and Merla [3] investigated the influence of the electrode material in drilling on different types of workpiece materials, as well as, the variation of the current peak. It was found that the effect of the electrode material on the geometry of the holes was not significant, In contrast, there was a noticeable effect on the wear and removal rates of the material.

Sharma et al. [4] also compared the rates of electrode removal and wear in electro-erosion machining with copper and brass electrodes in AISI 329 stainless steel drilling and noted that when compared with the copper electrode, the brass electrode undergoes wear because of its high electrical resistivity, low melting point and low thermal conductivity. Bandyopadhyay et al. [5] evaluated the geometric and metallurgical characteristics of the holes obtained by the pulsed laser drilling process in Inconel 718 and Ti-6Al-4V and determined that the geometry and quality of the holes is affected

mainly by the frequency and pulse energy parameters. Ahmad and Lajis [6] found that increasing the pulse current and pulse time in copper electrode erosion increases the surface roughness of the Inconel 718 machining.

The knowledge of the influence of the process control parameters on the characteristics of the holes is essential for the optimization of the process. The internal surface roughness of the holes directly influences the flow of fluids through them and the adhesion of particles inside them, directly affects the operation of components such as gas turbine vanes [4]–[16]. The objective of this study is to compare the manufacturing process with the influence of its working parameters on the internal roughness of the microholes.

2. EXPERIMENTAL PROCEDURES

The tests were conducted on samples of Inconel 718 - 30 mm long, 160 mm wide and 2.47 mm thick. Table 1 shows the input parameters for the EDM and Laser tests.

Table 1. Input parameters applied in the tests.

Small Hole EDM Drilling		Trepanning Laser Drilling	
Sample material:	Inconel 718	Laser type:	Nd:YAG
Electrode diameter (mm):	0.8	Wavelength (mm):	1.064
Dielectric fluid:	Deionized Water	Trepanning diameter (mm)	0.9
Electrode type:	Tubular	Assist gas	O ₂
Electrode material:	Brass; Copper	Frequency (Hz)	85

The selection of the variable parameters for the electro-erosion and laser was realized due to the greater influence of these parameters on the output variables such as finishing and roughness, as was seen in the literature [5] - [10], [12] - [16]. The difference between the diameter of the electrode and the diameter of the trepanation was caused by the high dilation of the electro-erosion processes, with intention to obtain microholes of 0.9 mm.

The bands for the electro-erosion of the variable parameters embedded in the equipment were from 4 A to 20 A for the current, 10 μ s to 50 μ s for pulse on time and 40% to 80% for the service factor. In laser drilling, the limits used were set at 0.6 J at 1.2 J for energy, 0.3 ms at 0.5 ms for pulse time and 50 mm / min at 70 mm / min for tangential speed. The parameter combinations follow those of the central compound model, shown in Table 2 which can be specified and divided into three parts [17]:

- The selected factorial planning was established as 2³, for the levels of the variables of +1 and -1;
- The star or axial planning, which for three variables, the assumed value for this planning ranged from +1.68 to -1.68;
- The center point was repeated three times. Thus, three replications were made at the central point for the experiments, which for all variables have an assumed value of 0.

Replicates of the microholes were made for both processes, making a total number of 102 microholes, 34 of which were made by laser trepanation, 34 by electro-erosion with a copper electrode and 34 with a brass electrode.

The samples were then cut with a Buehler Precision Cutter Model Isomet 4000 to allow surface roughness measurement with a Taylor Hobson Mitutoyo SurfTest SJ-410 Rough Meter and Taylor Hobson 3D CCI Lite, along the length of the inner wall of the microhole. Fig. 1 shows how the samples were cut.

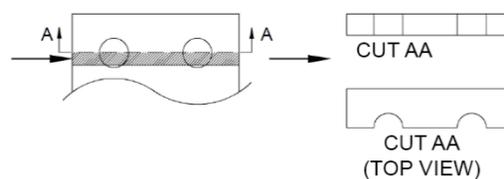


Figure 1 - Preparation of the sample of the hole channel for analysis.

The mean roughness (Ra) of the channel was obtained by three measurements made in each channel. In this way, it was possible to establish the standard deviation of the measurement. On the basis of the results obtained from Ra. With Design Expert 7.0 software, it was possible to plan the contour surfaces of the interaction between the variables of each drilling process.

Table 2. Experimental planning of the Laser and EDM drilling tests.

Hole	Trepanning Laser			Small Hole EDM Drilling		
	Trepanning Speed	Pulse width	Pulse Energy	Current	Pulse width	Duty Factor
1	-1 (VT2)	-1 (T2)	-1 (E2)	-1 (C2)	-1 (T2)	-1 (FS2)
2	1(VT4)	-1(T2)	-1 (E2)	1(C4)	-1(T2)	-1 (FS2)
3	-1 (VT2)	1(T4)	-1 (E2)	-1 (C2)	1(T4)	-1 (FS2)
4	1(VT4)	1(T4)	-1 (E2)	1(C4)	1(T4)	-1 (FS2)
5	-1 (VT2)	-1 (T2)	1 (E4)	-1 (C2)	-1 (T2)	1 (FS4)
6	1(VT4)	-1(T2)	1 (E4)	1(C4)	-1(T2)	1 (FS4)
7	-1 (VT2)	1(T4)	1 (E4)	-1 (C2)	1(T4)	1 (FS4)
8	1(VT4)	1(T4)	1 (E4)	1(C4)	1(T4)	1 (FS4)
9	-1.68 (VT1)	0 (T3)	0 (E3)	-1.68 (C1)	0 (T3)	0 (FS3)
10	1.68(VT5)	0 (T3)	0 (E3)	1.68(C5)	0 (T3)	0 (FS3)
11	0 (VT3)	-1.68 (T1)	0 (E3)	0 (C3)	-1.68 (T1)	0 (FS3)
12	0 (VT3)	1.68 (T5)	0 (E3)	0 (C3)	1.68 (T5)	0 (FS3)
13	0 (VT3)	0 (T3)	-1.68 (E1)	0 (C3)	0 (T3)	-1.68 (FS1)
14	0 (VT3)	0 (T3)	1.68 (E5)	0 (C3)	0 (T3)	1.68 (FS5)
15	0 (VT3)	0 (T3)	0 (E3)	0 (C3)	0 (T3)	0 (FS3)
16	0 (VT3)	0 (T3)	0 (E3)	0 (C3)	0 (T3)	0 (FS3)
17	0 (VT3)	0 (T3)	0 (E3)	0 (C3)	0 (T3)	0 (FS3)

3. RESULTS AND DISCUSSION

The Ra surface roughness for the microholes obtained by electro-erosion with copper and brass electrodes is shown in Fig. 2 (a) and the trepanning laser drilling in Fig 2 (b). It can be seen that the microholes obtained by the laser process had less surface roughness than the microholes obtained through electro-erosion.

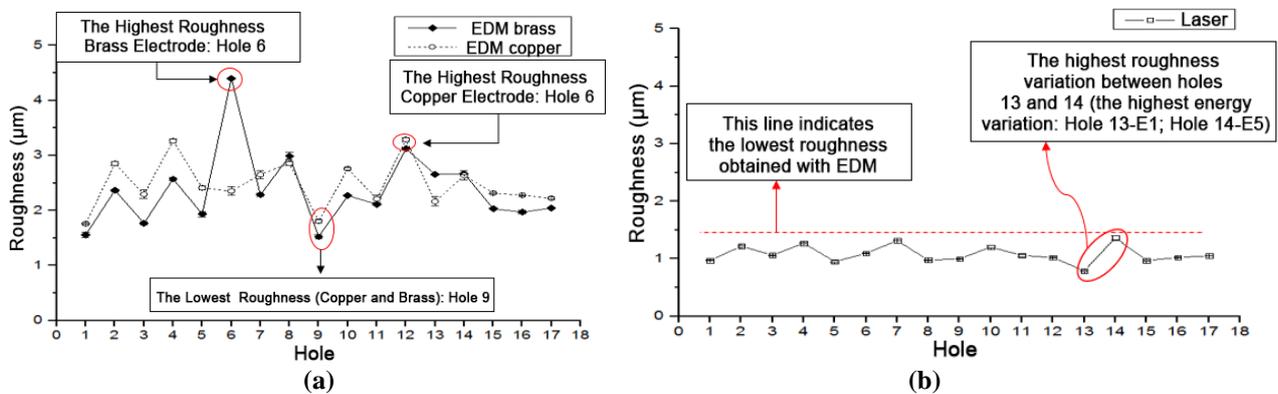


Figure 2. Variations of the roughness with EDM drilling (a) and Laser drilling (b).

In micro-drilling obtained by electro-erosion, it was observed that the microhole 9 was obtained the lowest value of roughness, for both electrode materials. The microhole 9 was manufactured with the lowest current (C1) used in the electro-erosion tests. Li et al. [9] found that, the lower current value, produce lower roughness surface for the surface machined by electro-erosion. It was also observed that when the current was changed to the higher intensity level (C5), in microhole 10, the roughness increased more than with the microhole 9. The roughness peak described in microhole 6, which is made from a brass electrode, can be explained by the discharge of direct current from the small pulse interval.

In holes made with less current, the particle size removed from the component during the machining is also smaller, and as a result, there is a reduction in the concentration of spatter and craters on the surface of the channel, which directly affect the roughness of the machined surface. Microhole 12 showed the highest degree of roughness in the microdrilling with a copper electrode. In the microhole 12, the pulse time is at the highest level (TP5), the high degree of roughness is explained by the increased particle size, or chip, which is removed by the longest pulse time. This higher pulse time increases the crater and the amount of spatter in the channel.

It can also be noticed that in the case of microholes 15, 16 and 17, which represent the central point of the experimental planning, the roughness tends to remain constant, with intermediate values of the roughness.

The morphology of the microholes can be characterized by: spatter, craters and surface homogeneity. In Fig. 3, the arrows with solid lines indicate the presence of craters, the arrows with dashed lines indicate the presence of spatter, and the ellipses circumvent the regions that have homogeneous surfaces. The images are of the microholes 1 and 2 obtained with brass electrodes (Fig. 3 (a)) and copper (Fig. 3 (b)). The presence of spatter and craters can be found in a higher concentration in microhole 2 (C4) than microhole 1 (C2). Another feature is the presence of larger regions of homogeneous surfaces in the channel of microhole 1.

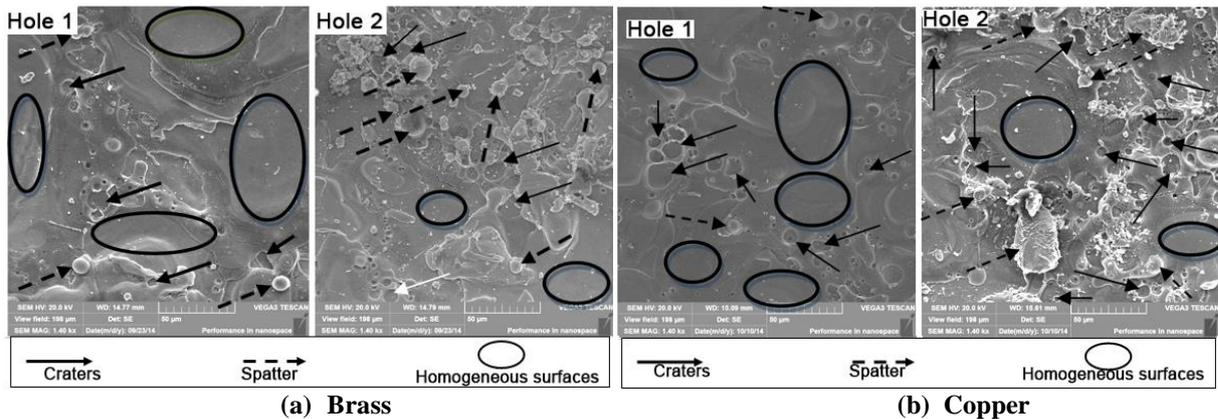


Figure 3. Morphology of hole walls: 1 (current C2) and 2 (current C4) obtained with electrodes of (a) brass and (b) copper. MEV 700x

The higher incidence of spatter and crater in the microholes with parameter 2, carried out with copper and brass electrodes, certainly influenced the roughness of these microholes. When the roughness values of the microholes 1 and 2, obtained with brass electrodes and copper electrodes, are compared, it can be observed that the roughness of microhole 2 is higher than the roughness of microhole 1, for both electrode materials, as shown in Table 2.

Table 2. Roughness of Holes 1 and 2 obtained by EDM

Electrode Material	Roughness (Ra) Hole 1 (µm)	Roughness (Ra) Hole 2 (µm)
Brass	1.556 ± 0.047	2.366 ± 0.023
Copper	1.758 ± 0.013	2.855 ± 0.037

When drilling is carried out with a brass electrode it can be observed that there is a greater variation of the roughness with input parameters, than copper electrode. In copper, the red regions indicates the highest roughness values, have a larger area in the response surface (Fig. 6) than when drilling with a brass electrode.

According to Li et al. [9], the increased roughness, which occurs as the result of a greater current discharge, can be explained by increased erosion, and the resulting larger amount of chips and spatter present on the surface of the machined material.

In laser drilling, the roughness reaches 1.5 µm when there is a combination of a longer pulse time and higher energy rates, for electro-erosion drilling process the roughness can reach up to 4.5 µm if highest current value and pulse time are combined.

The variation in roughness was lower for laser process than electro-erosion process. The combination of parameters for hole 10, obtained by electroerosion process, led to the lowest roughness value, similar with the values obtained by the laser drilling process.

In both processes, it was confirmed that the combination of greater pulse time and higher energy (electric current and energy laser drilling), results in worse conditions for surface finishing. This is due to the fact that the greater the energy and the longer the time needed for the material to be removed, the larger the surface crater and the larger the particle size of the material removed from the base metal. If this removed material is not expelled by the fluid inside the channel, this particle will resolidify on the machined surface and form spattering, which changes the relief formation of the machined surface.

The morphology of the channel can be evaluated by comparing the different regions of the same channel. Figure 4, (a) and (b) shows the channel of the microhole 1, obtained by electro-erosion with a copper electrode, where the region "a" represents the region at the end of the machining and "b" shows the region at the beginning of the microdrilling.

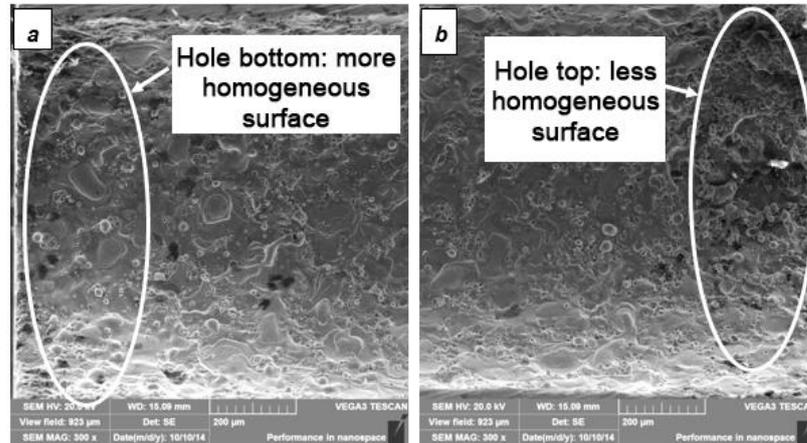


Figure 4. Comparison of the morphology in different regions of Hole Channel 1 made by EDM: a) the surface closest to the end (bottom) of the microdrilling ; B) the surface closest to the beginning (top) of the microdrilling

At the beginning of the channel the morphology is more irregular. This irregularity can be explained by the region that concentrates more molten and resolidified material during the microdrilling process. The resolidified material generate spatters, which is responsible for increasing the irregularity of the surface.

Another explanation for the spatter increase in the region close to the beginning of the drilling, is the time required for the discharge of energy, responsible for the removal of the material. During the whole electro-erosion process , the formation of the plasma channel, responsible for the heating and melting of the material, occurs in the beginning of the machining region. This is due to the proximity between the outside diameter of the electrode and the wall of the microhole being machined. As it is the region that remains heated, melted and resolidified by the action of the dielectric fluid, the irregularity in this region is greater, than the regions closer to the end of the machining.

In the final region of the microhole, there is a reduction of resolidified material, since the time for the discharge of energy in this region is smaller, and hence, most of the molten material is removed during the machining.

Fig. 5 shows the channels of the microholes 13 (Fig. 5a) and 14 (Fig. 5b) in the trephine laser drilling. It can be observed that there is a higher concentration of spatter in the channel of microhole 14 than in the channel of microhole 13. This may be due to the fact that the concentration of energy during the removal of material in Microhole 14, was higher than the energy of microhole 13. As more material was melted, the flow of the oxygen was not sufficient to remove all the molten material. When this occurs, the oxygen acts as a fluid that can assist in the cooling of the material by convection, and thus result in the resolidification of these material. The resolidified material has an irregular shape that increases the roughness of the microhole surface.

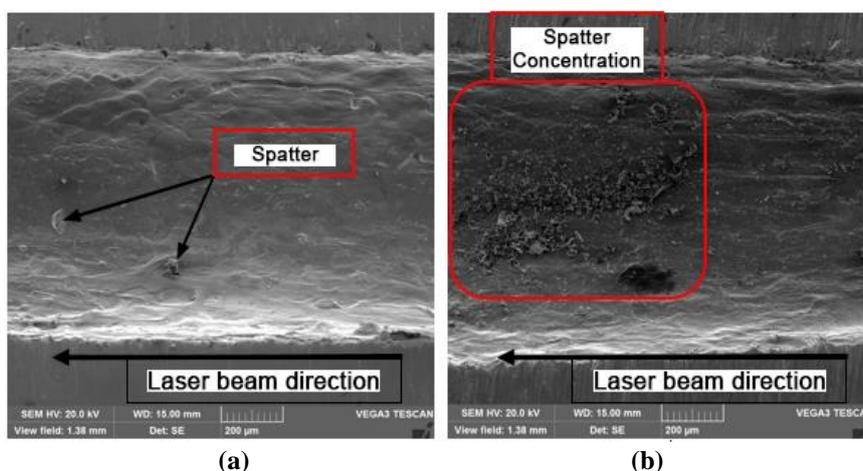


Figure 5. Comparison of the hole channels 13 (a) and 14 (b). Hole 13 was manufactured with the lowest pulse energy (E1) and Hole 14 with the highest pulse energy (E5). MEV 100x.

Another feature that can be highlighted in the images of Fig. 5 concerns to the position of the spatter in Microhole 14. It can be noted that for both microholes, the concentration of spatter increases from the intermediate region to the end of the Machining. The reason for this is that oxygen tends to expel the molten material towards the laser beam. If the active

oxygen is not sufficient for the complete removal of the material, it tends to push it to a region near the end of the machining, which causes the higher concentration of the spatter in the region closest to the end of the machining. This situation directly reflects in the higher roughness values of the channel.

Finally, when the laser and electroerosion drilling processes are compared, (as can be seen in Fig. 6) the interaction of the input parameters results in a modification of the roughness of the microholes. In this diagram, the response surfaces obtained from the measured roughness are shown. These graphs represent the tendency of the roughness with the combinations of the parameters used. Blue regions indicates the tendency to obtain lower levels of roughness, and the red regions to obtain the highest levels of roughness. Nominal roughness values are shown in square boxes inside the graphs.

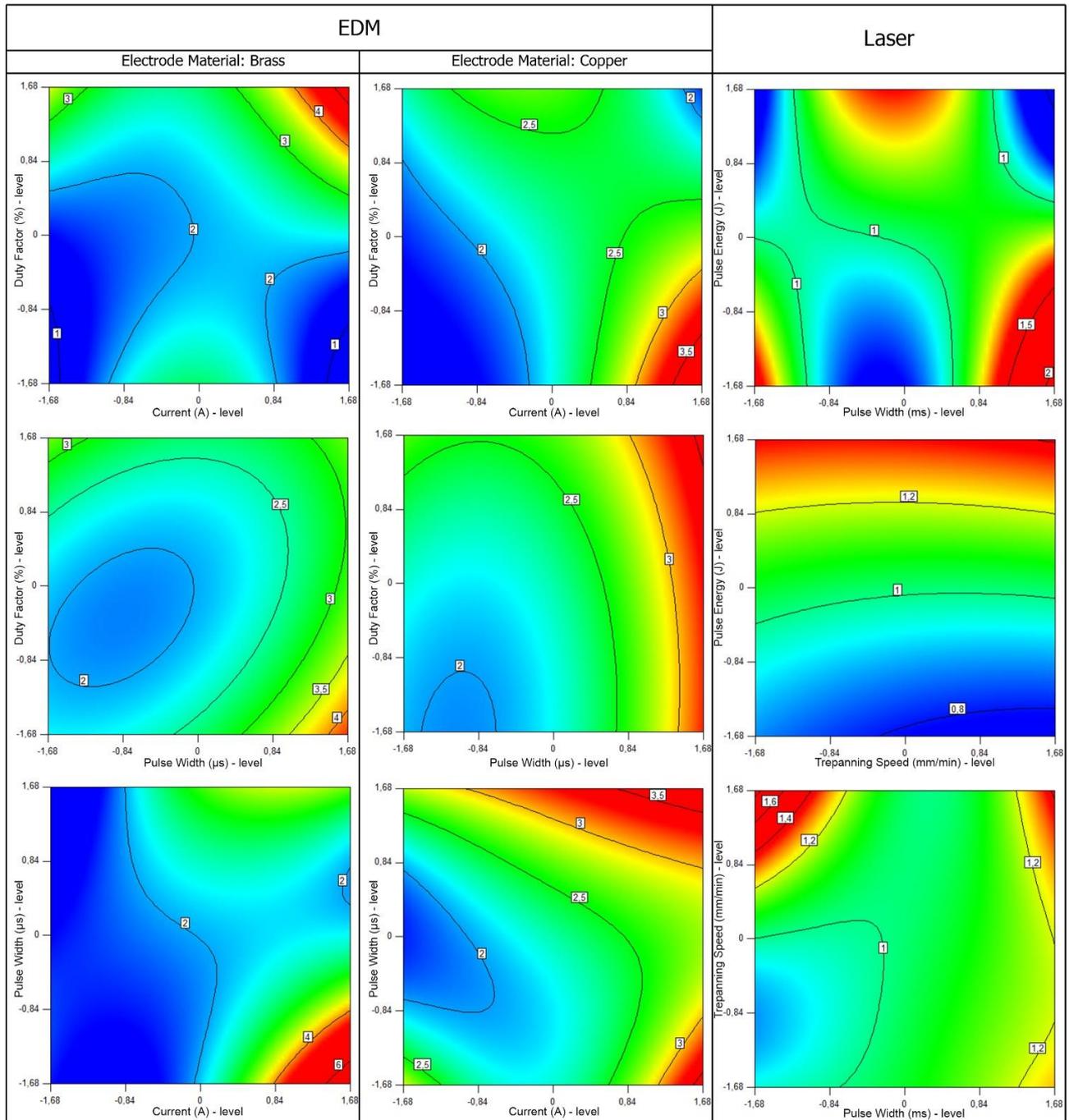


Figure 6. Roughness response surfaces for laser and EDM drilling processes

Table 3 shows the results of maximum and minimum roughness obtained from the combinations of the interactions between the input parameters of each analyzed microhole.

Table 3. Summary of the results of maximum and minimum roughness in the interactions of Fig.4

EDM (BRASS ELECTRODE)	Level of Minimum Roughness	Minimum Roughness (µm)	Level of Maximum Roughness	Maximum Roughness (µm)
Current x Duty Factor	Current of +1.68 or -1.68	1	Current +1.68	4
	Duty Factor from -1.68 to 0		Duty Factor +1.68	
Pulse Width x Duty Factor	Pulse Width from -1.68 to 0	2	Pulse Width +1.68	4
	Duty Factor from -1.68 to 0		Duty Factor -1.68	
Current x Pulse Width	Current -1,68	2	Current +1.68	4.5
	Pulse Width from -1.68 to +1.68		Pulse Width -1.68	
EDM (COPPER ELECTRODE)	Minimum Roughness Level	Minimum Roughness (µm)	Maximum Roughness Level	Maximum Roughness (µm)
Current x Duty Factor	Current -1.68	2	Current +1.68	3.5
	Duty Factor -1.68		Duty Factor -1.68	
Pulse Width x Duty Factor	Pulse Width -1.68	2	Pulse Width +1.68	3.5
	Duty Factor -1.68		Duty Factor from -1.68 to +1.68	
Current x Pulse Width	Current -1.68	2	Current +1.68	3.5
	Pulse Width from -1.68 to +1.68		Pulse Width of -1.68 or +1.68	
LASER	Minimum Roughness Level	Minimum Roughness (µm)	Maximum Roughness Level	Maximum Roughness (µm)
Pulse Width x Pulse Energy	Pulse Width +1.68	<1	Pulse Width +1.68	1.5
	Pulse Energy +1.68		Pulse Energy -1.68	
Pulse Energy x Trepanning Speed	Pulse Energy -1.68	0.8	Pulse Energy +1.68	>1.2
	Trepanning Speed from 0 to +1.68		Trepanning Speed from -1.68 to +1.68	
Pulse Width x Trepanning Speed	Pulse Width of -1.68	<1	Pulse Width -1.68	>1.6
	Trepanning Speed from -1.68 to 0		Trepanning Speed +1.68	

4. CONCLUSION

On the basis of the obtained results, the influence of the input parameters analyzed in each process, the roughness and the morphology of the manufactured microholes, were determined. The main factors involved were:

1. It was observed that the microholes with higher concentration of spatter and craters in the channel were the micro holes 6 and 12 for EDM, and microhole 14 for laser drilling). The average roughness of the holes made by laser process was lower than the roughness obtained by the electro-erosion processes.
2. The position of the highest concentration of spatter in the laser microholes shows that the oxygen flow, responsible for the removal of the materials, was not enough, and acted as a fluid that helps the cooling of the channel, increasing the solidification of the material and the the roughness of the microholes.
3. In the laser drilling process, it was confirmed that microholes obtained with higher energy shows higher roughness values, caused by the larger number of craters and spatters.
4. When fast EDM drilling is employed, the roughness is greater in holes made with high current levels, due to the formation of larger craters in the machined surface. In drilling with a cooper electrode, the degree of variation in roughness, with the working parameters, is smaller than when drilling with brass electrodes. For the majority of the parameters, copper electrodes showed greater surface roughness than obtained with brass electrode as well as the laser drilling process.
5. It was found that in laser drilling, the presence of splashes inside the channels, is less than occurs with the channels obtained by electro-erosion process. This characteristic results in the lower roughness of the microholes obtained in the laser than was the case with the microholes obtained by electro-erosion.

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