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Improvement of EDM performance in high-aspect ratio slot machining using multi-holed electrodes

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ABSTRACT

Machining of high-aspect ratio slots is a common operation in industry, particularly in the mold and die and aerospace sectors. Electrical Discharge Machining (EDM) is a competitive technology for this operation, since it does not depend on material hardness and can fulfill strict geometrical requirements. However, due to debris accumulation in the narrow gap, the machining depth for stable machining is limited. The present work includes original findings about the influence of machined holes on flushing efficiency. Different configurations for this basic approach have been proposed and their performance discussed in terms of machining time and electrode wear. A remarkable and original finding is that continuous pockets or open holes are much better than the separated or closed holes. Furthermore, the paper shows that a sudden change in material removal rate occurs when the vacant spaces of the holes are sunk in the slot. A deeper insight into the EDM phenomena has been achieved through a study of discharge parameters, by analyzing discharge frequency, duty factor, discharge delay time and discharge off-time. In this study, using the proposed electrode reduced the process time by as much as 65% in the machining of 10 mm depth slots. Moreover, machining stability can be guaranteed if the flushing pockets machined on the electrode go through the whole depth of the machine.

1. Introduction

Electrical discharge machining (EDM) has become an indispensable technology in the manufacture of high-aspect ratio slots. One of the great advantages of this technology in comparison with conventional manufacturing processes is that in EDM there is no contact between the electrode and work piece, which avoids mechanical stresses, chatter, and vibration problems during machining [1]. Moreover, material hardness is not a limitation, which has implied benefits in comparison with the conventional machining method, particularly in the machining of high-aspect ratio slots in difficult-to-machine materials.

Manufacturing of deep slots is a common operation in industry, with special focus on two sectors: mold and die industry and aerospace industry. In the former, for instance, narrow slots are machined in the mold in order to provide thin strengthening ribs. In the latter, due to the working requirements of turbine engines, high temperature resistant materials are used, such as Titanium-base or Nickel-base alloys. As an example, when it comes to machining the slots used to join the NGVs (*Nozzle Guided Vanes*), EDM is currently regarded as the most competitive solution [2].

However, the EDM machining of high-depth slots is not an easy task. The main drawback is that there is a high concentration of discharges in the bottom section of the electrode, and that as the depth increases debris evacuation becomes difficult or even impossible. As a consequence, the stability of the process becomes affected and the material removal rate decreases [3].

Recent studies can be found in the scientific literature concerning the optimization of the EDM process of high-aspect ratio slots. Much of this work has focused on aerospace applications, mainly due to the high competitiveness of this market, in which the key objective is to reduce the machining time or the total production time.

A number of researchers have explored the effectiveness of choosing different EDM process parameters and electrode material. For instance, Uhlmann and Domingos [4] reduced the machining time of 11 mm depth slots with an electrode of 89.50 mm^2 and the discharge area from 48 min to 21.9 min by adjusting process parameters. Ayesta et al. [5] analyzed the influence of process parameters with a discharge area of 40 mm^2 and depth of 6.5 mm. They concluded that shorter machining times were obtained by a combination of high discharge current, long pulse duration, and low servo voltage. In terms of electrode material,

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Aas [6] compared the machining outputs of two types of graphite qualities. From these experiments, it was concluded that if productivity is a priority, a larger particle grain size is more appropriate.

However, as reported by Klocke et al. [7], due to debris particle concentration in the narrow gap, gap temperature, and ionization conditions of the dielectric fluid, stability of the process cannot be guaranteed. During the early stage of machining, debris evacuation is efficient and as a consequence machining is stable. Nevertheless, when the depth increases, debris particles become stuck in the narrow gap and the process becomes unstable, resulting in a dramatic decrease in the rate at which material can be removed. This phenomenon was also reported by Obaciu et al. [8] when comparing the machining performance of two different work piece materials. They observed that as the erosion depth increases, the material removal rate decreases and the number or short circuits increases. Therefore, the main cause of the increase in process time with the machine depth lies in the accumulation of debris within the narrow gap, which compromises the stability of the process. As a consequence, it is expected that an enhancement of flushing conditions will contribute to the optimization of the process.

Various strategies have been developed in order to improve debris removal from the working gap. Uhlmann and Domingos developed a vibration-assisted EDM-machining technology and they observed improvements in material removal as well as in electrode wear. This technology was validated by machining a 11 mm depth slot; with the optimization of frequency and amplitude, an increase of 11% of the material removal rate was achieved [9]. However, they observed that once the erosion depth exceeded 8 mm the machining performance decreased [10].

A further technology that brings improvement in terms of flushing conditions is the use of jump motion by linear motor equipped machines. Cetin et al. [11] studied the effect of jump motion when using a 10 mm diameter cylindrical electrode. They observed that the electrode jump height is the most relevant factor in machining speed. However, as reported by Liao et al. [12], the work presented in [11] does not take into account the fact that the effectiveness of debris evacuations is related to the geometry. Debris evacuation becomes more difficult when working with thin electrodes than with square section electrodes.

In practice, both vibration-assisted EDM-machining and the use of high-acceleration linear motors require the use of extra equipment, which is not available to many users.

The idea developed in the present research work emerges from the similarities of the problem of EDM of high-aspect ratio slots with a recent application of EDM technology for SiC slicing using foil electrode, which has been described in [13]. They found that if the slicing was conducted by feeding the thin foil electrode in Z direction, the cutting speed was improved by 23% when using an electrode with holes. The improved machining performance was attributed to the chip pocketing effect of holes.

The most important and original findings of the present work are related to the geometry and the position of the holes. A remarkable and original finding is that continuous pockets or open holes are much better than the separated or closed holes. Furthermore, the paper shows that a sudden change in material removal rate occurs when the vacant spaces of the holes are sunk in the slot. In Section 2 the experimental set-up and the test methodology used for obtaining the optimum electrode design is described. In Section 3 a discussion of the results is presented in terms of machining time and electrode wear. A deeper insight into the performance is addressed in Section 4 through a study of discharge parameters, in which discharge frequency, duty factor, discharge delay time, and discharge off-time have been analyzed. A reduced process time as high as 65% in the machining of 10 mm depth slots has been achieved by using the proposed electrode. The results show that machining stability can be guaranteed if the flushing pockets machined on the electrode go through the entire depth of the machine.

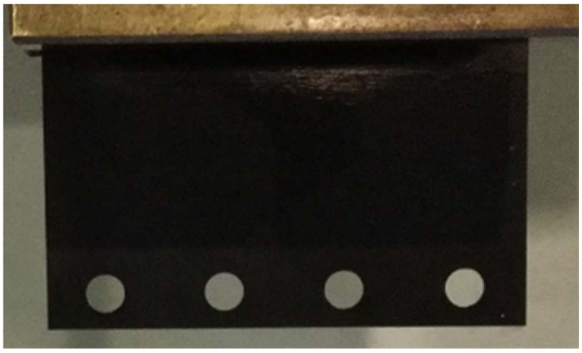

Fig. 1. Specially designed graphite electrode for slot machining.

2. Experimental set-up and test methodology

The objective of the experiments was to assess the improvement in performance, if any, of the EDM process of high-aspect ratio slots when a specially designed electrode is used. The new electrode has a number of holes in its lateral faces that are expected to contribute to effective debris evacuation during the process.

The experiments were carried out under industrial conditions on an ONA CS300 sinking EDM machine. The generator of the machine tool used in the experiments is an iso-energetic generator. This means that during the machining process the generator attempts to maintain discharge current (I) and pulse on time (t_{on}) at constant values. Moreover, in order to avoid inefficient discharges, such as arc and short-circuits, the pulse generator controls the t_{off} value.

The work piece material was F114 structural steel. In this work, POCO EDM3 electrodes were prepared with dimensions of 0.8 mm in thickness and a length of 50 mm. As stated previously, flushing holes were machined on the lateral faces of the electrodes. Fig. 1 shows an example of such an electrode.

Since the objective was to test the efficiency of the new proposal, the conditions of the EDM process were not manipulated during this study. Instead, they were taken from a previous research study [5] in which optimization of process variables for the EDM machining of high-aspect ratio slots was addressed by using Design of Experiments techniques. Therefore, the process conditions have been taken from the above cited reference and they are shown in Table 1. Jump motion has not been used during the experiments.

With the objective of enhancing the flushing condition of the narrow gap, three effects were studied: the effect of flushing holes diameters, positioning of the flushing holes, and geometry of the flushing cavity.

With the aim of studying the repeatability of the process and given that in the industry the same electrode is used for machining a set of slots, in the present work 5 slots were machined for each experimental condition. A detailed explanation of the experimental method for analyzing each effect is presented in the following sections.

2.1. Influence of hole diameter

In order to study the impact of the diameter of the flushing holes on

Table 1
Machining and experimental conditions.

Working fluid	EDM oil
Polarity	+
Open voltage	120 [V]
Discharge current	48 [A]
Discharge duration	89 [μs]
Preset off-time	179 [μs]
Servo voltage	57 [V]

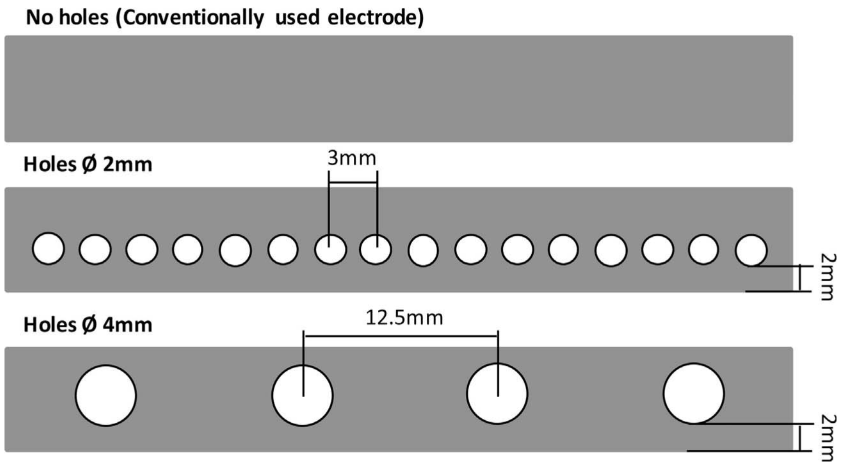

Fig. 2. Test definition for analyzing the effect of holes.

machining performance, three different electrode designs were compared: conventionally used electrode (without holes), electrode with holes of 2 mm, and electrode with holes of 4 mm. Fig. 2 shows a scheme of the electrodes. In both cases the reduction in the area of the electrode material was maintained constant. This allows, on the one hand, to study separately the effect of hole diameter; and on the other hand, higher performance can be expected, because it is considered that the enhancement of flushing conditions is due to the chip pocketing effect of the holes.

In order to compare the results, a machining depth of 6.5 mm was considered, which is a reasonable machining depth in the machining of the lateral faces of NGVs.

2.2. *Influence of positioning of the holes in the electrode*

In addition, the influence of the position of the flushing holes with respect to the discharge area was investigated. In this case, the diameter of the flushing holes was of 4 mm and the machining depth was maintained as 6.5 mm. Fig. 3 shows the scheme of the electrode designs compared. Additionally, machining flushing holes to a distance of 1 mm from discharge area was considered. However, due to the poor machining conditions, the cycle of 5 slots was not completed.

2.3. *Influence of hole geometry*

As discussed, an increase in the machining depth implies greater difficulties in terms of the flushing conditions and debris evacuation. Therefore, in order to determine the optimum electrode design, two electrode designs were proposed when machining at a depth of 10 mm. The electrode designs compared are shown in Fig. 4. The main objective was to understand which design – two rows of flushing holes in staggered rows or a pocket-flushing cavity – results in better machining performance.

Additionally, the influence of the chip pocketing effect of pockets on machining time was studied at a depth of 15 mm and 25 mm.

2.4. *Process outputs*

With the aim of analyzing the effect of flushing holes on the machining performance, the machining time and the electrode wear were compared.

When machining high-aspect ratio slots, an increase in machining depth causes the process to lose stability, whilst the rate of material removal decreases. This indicates that the rate of material removal is not constant throughout the process. Hence, in the present work machining time was considered as an output parameter, which refers to the average time of the five slots. Moreover, the standard deviation was represented.

Electrode wear was characterized by three outputs: electrode edge radius, lost length of electrode, and electrode lateral wear. Fig. 5 illustrates the outputs measured for characterizing electrode wear. Measurements of edge radius and length loss were taken after each slot, whilst lateral wear of the electrode was measured after completing the machining of the 5 slots.

Electrode edge radius represents the average radius of both edges and it was measured using a profile projector (Mitutoyo PJ-3000F). Electrode length loss was measured in the machine tool by comparing the length of the electrode both before and after each operation. The

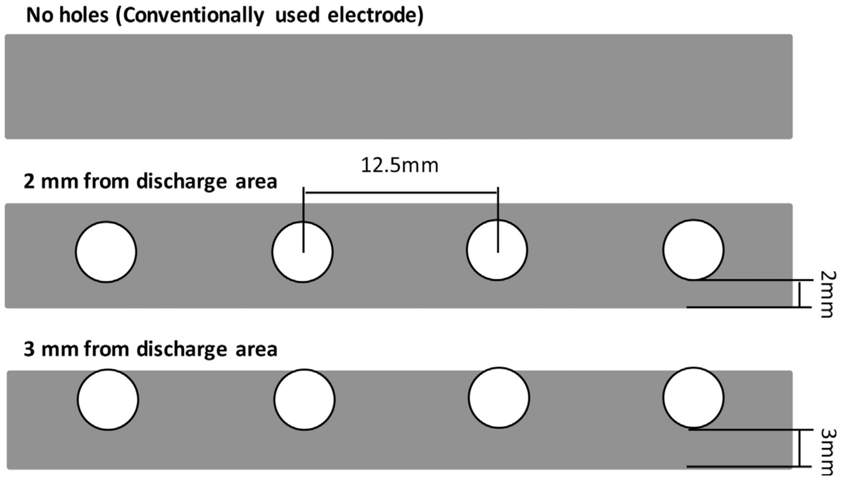

Fig. 3. Test definition for analyzing the influence of positioning of the holes in the electrode.

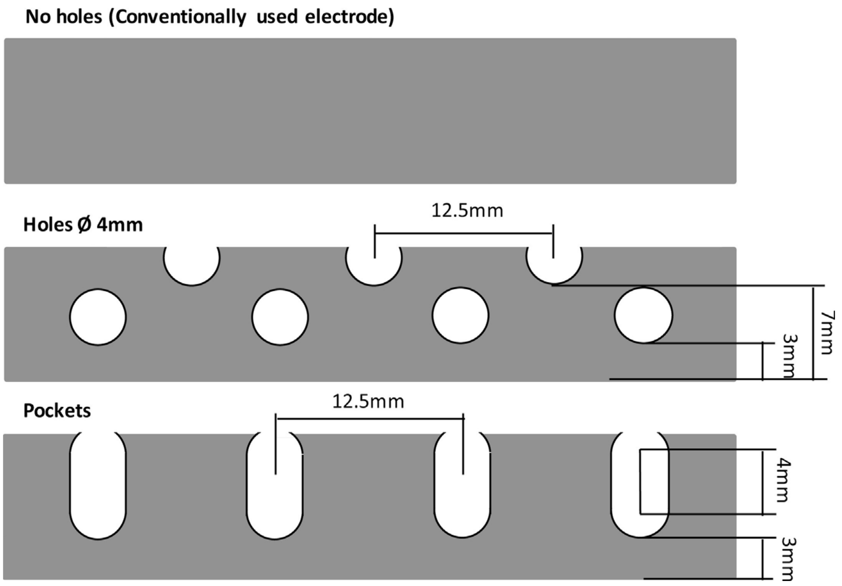

Fig. 4. Test definition for improving hole geometry.

measurement was taken at three points and the average value was represented. Moreover, with the objective of analyzing the concavity effect of the electrode, the lateral section of the electrode was measured using a 3D optical surface metrology system (LEICA DCM 3D).

3. Results and discussion

As explained in the previous section, various electrode designs were considered in this study, so that three different effects could be analyzed: effect of flushing hole diameter, effect of flushing hole position from the discharge gap and the effect of flushing hole geometry.

In this section each effect is discussed separately in terms of machining time, electrode wear radius and electrode lost length. Results regarding lateral electrode wear are also considered.

3.1. Effect of the diameter of the flushing holes machined on the electrode

This section compares the machining performance of a conventionally used electrode (No holes), electrode with holes of 2 mm (Holes ø2 mm) and electrode with holes of 4 mm (Holes ø4 mm). As mentioned previously, the area reduction of the electrode was maintained constant in both combinations. The preset machining depth for each slot was 6.5 mm.

Fig. 6a shows the average machine time as well as the standard deviation between the five slots of the machined cycle. The impact of holes on the machining time is clear, given the improvement in machining time. With holes of 2 mm in diameter the improvement is 20% and for holes of 4 mm the improvement is 48%. This is attributed to the chip pocketing effect of holes, which improves the flushing conditions in a narrow gap. It is therefore clear that the strategy of machining holes in the electrode yields considerable benefits in terms of productivity.

Electrode wear is also of primary importance in this type of EDM operation. Fig. 6b shows the evolution of electrode edge radius during the experiments with the different electrode geometries. As previously observed by Mohri et al. [14] the increase in corner radius occurs at the early stages of machining. In our experiments the maximum change in radius occurs during the machining of the first slot. This is because discharge concentration – which leads to an increase in local electrode temperature – is higher at sharp edges. No significant differences were observed between the different experiments in terms of evolution of edge radius. However, it should be noted that significant differences are observed in the evolution of electrode lost length (see Fig. 6c). The use of the electrode with flushing holes leads to wear being reduced by 65%, regardless of the diameter of flushing holes used. Therefore, it appears that loss of electrode length is directly related to machining time.

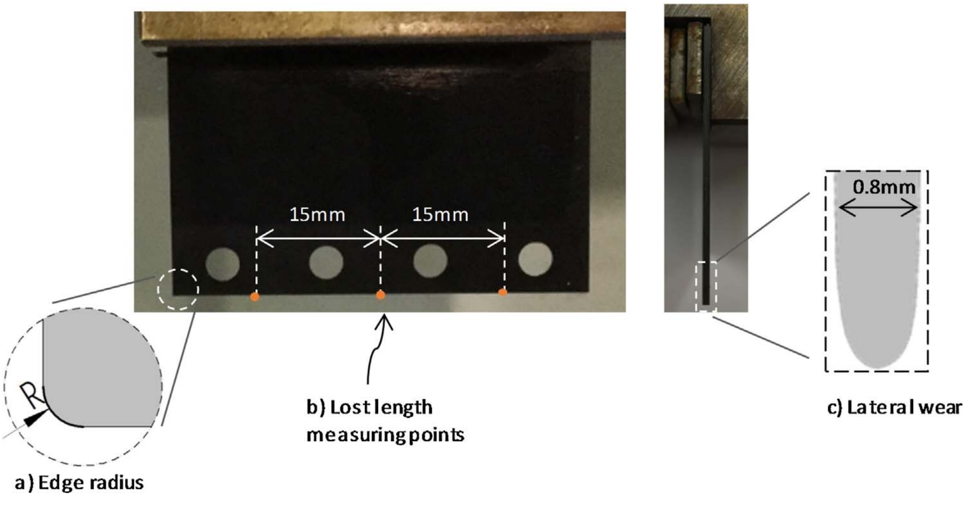

Fig. 5. Characterization of electrode wear. a) Edge radius; b) length loss; c) Lateral wear.

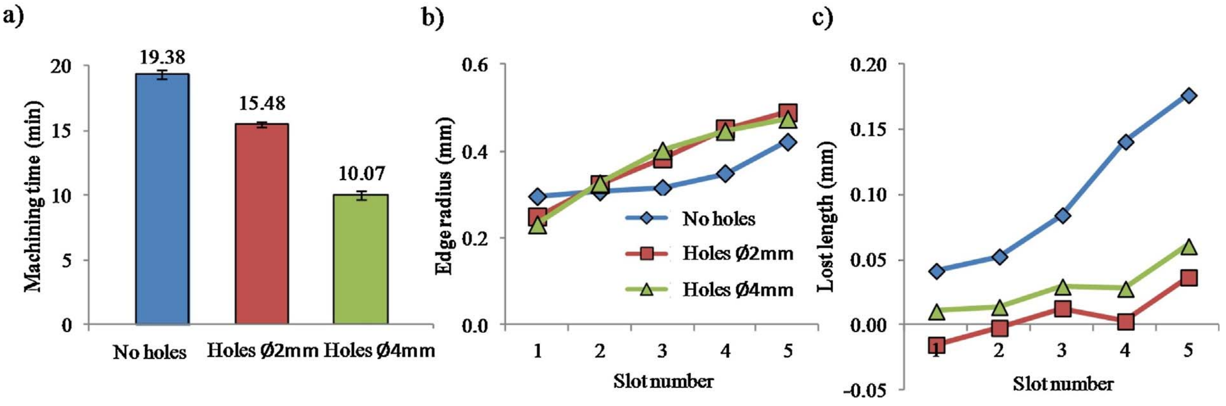

Fig. 6. Influence of flushing hole diameter in terms of: a) Machining time, b) Edge radius, c) Length loss.

3.2. Effect of the position of flushing holes with respect to discharge area

In this section the influence of the position of the flushing holes from the discharge area is analyzed. The experiments aimed to compare the machining performance when using a conventional electrode (No holes), an electrode with flushing holes of 4 mm diameter at a distance of 2 mm from the discharge area (2 mm) and an electrode with flushing holes of 4 mm diameter at a distance of 3 mm from the discharge area (3 mm). An additional test was conducted with holes at a distance of 1 mm from the discharge area. However, the results in this latter case were very poor, and they have therefore not been included in the discussion.

The data plotted in Fig. 7a indicate that machining time can be improved by machining the flushing holes of the electrode at a distance of 3 mm from the discharge area. In fact, an improvement of 57% is achieved when compared with the machining time consumed by the electrode with no holes. Even when comparing with the results in Fig. 6 an improvement of 17% was observed. This effect was attributed to the enhancement of flushing conditions. Moreover, upon inspection of the displacement of the machine axis when machining a single slot (see Fig. 8), it can be concluded that the machining process is very stable with this new configuration.

Fig. 8 shows the evolution of machining time versus slot depth for three different electrode geometries: with no holes, with holes at 2 mm from electrode edge and with holes at 3 mm from electrode edge. According to the results, machining becomes unstable at a machining depth of 4 mm when the conventional electrode is used. At that depth, the electrode retracts and the material removal rate reduces dramatically. Stability is increased by locating holes at 2 mm from electrode edge, but the same effect of electrode retraction is observed when flushing holes are completely inside the slot. When holes are located at 3 mm from electrode edge, stability is ensured all along the operation. The issue of stability will be further discussed in the following section (see Fig. 10).

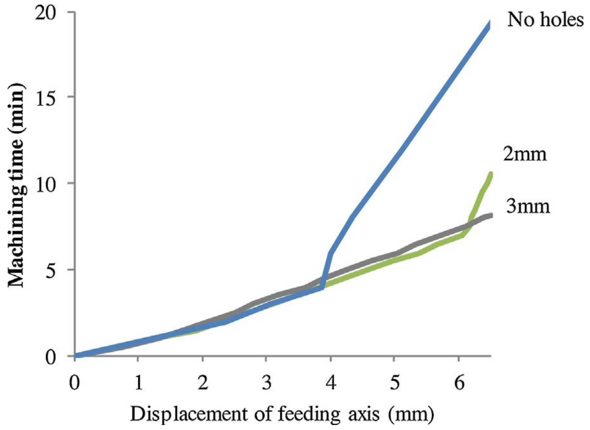

Fig. 8. Comparison of the displacement of feeding axis vs. machining time with the three different electrode designs.

In terms of electrode wear at the edge radius (see Fig. 7b), no remarkable differences have been found. However, Fig. 7c clearly indicates that loss of electrode length decreases when flushing holes are machined at a distance of 3 mm from the edge of the electrode, which maintains the relationship with the machining time. A longer machining time means that the electrode is exposed for a longer time to high temperatures and, given that the area of discharge is small, this can have a considerable impact on electrode wear.

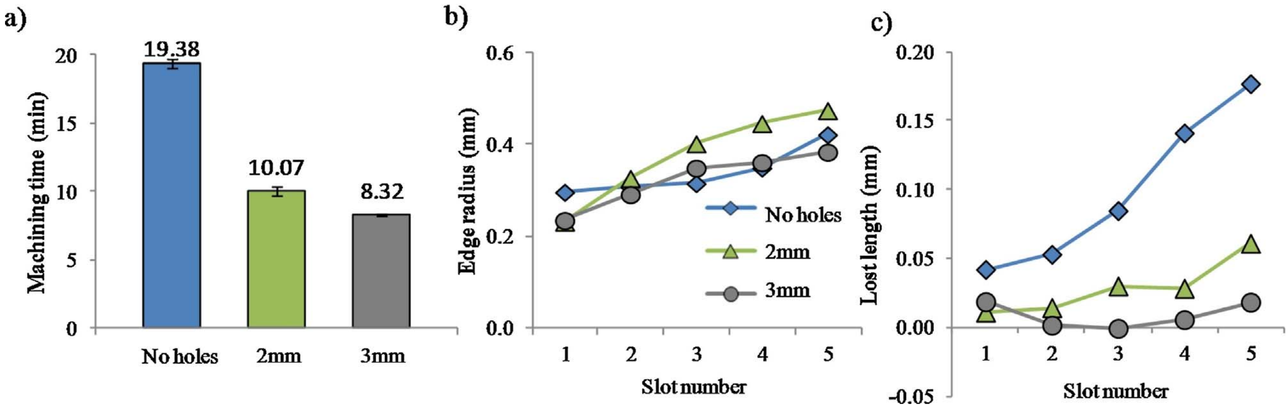

Fig. 7. Influence of position of flushing holes from discharge area in terms of: a) Machining time, b) Edge radius, c) Lost length.

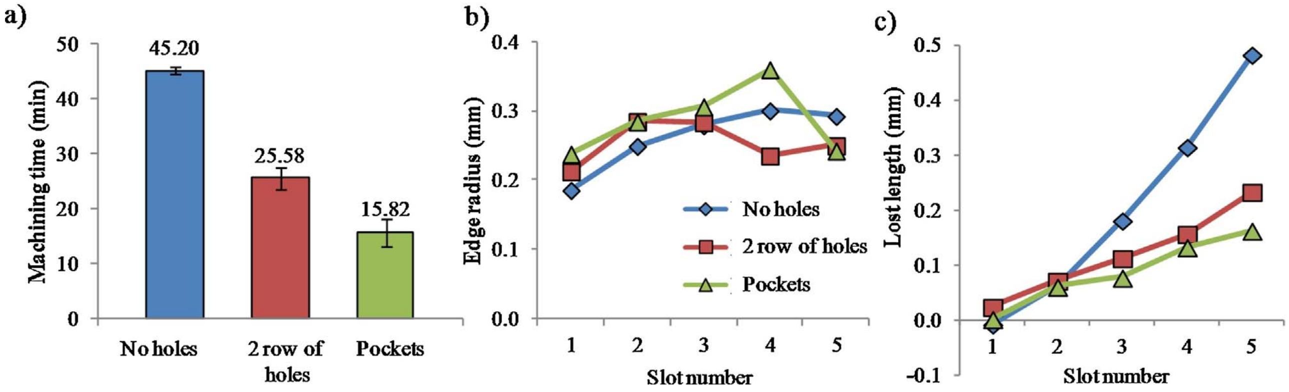

Fig. 9. Influence of flushing hole geometry in terms of: a) Machining time, b) Edge radius, c) Lost length.

3.3. Effect of flushing hole geometry

From the results described above it was concluded that machining stability could be guaranteed for a depth of 6.5 mm if the holes penetrate the entire depth of the machining operation (see Fig. 8). In this section, a machining depth of 10 mm was chosen and two electrode designs were proposed: two staggered rows of holes of 4 mm diameter (2 rows of holes) and open holes (Pockets). The main goal was to understand whether the holes need to penetrate the entire machining depth in order to enhance machining performance.

Fig. 9a represents machining time for the three experiments. Both staggered rows and pockets dramatically reduce machining time, but the best performance was obtained with the pockets design. With the electrode with two staggered rows of holes the improvement was 43% and with pockets this improvement was 65%. The reason for this, as observed in Fig. 10, is that after the first row of holes is positioned inside the slot, there is a decrease in stability and hence material removal. In contrast, stability is ensured throughout the entire machining depth when using the electrode with pockets.

With respect to electrode wear (Fig. 9b and c), a similar behavior to that observed in the previous experiments can be noticed: no significant differences were recorded in the development of wear at the edge radius, but the loss in electrode length was reduced by 66% when using the proposed new designs. Moreover, a decrease of electrode edge radius is observed in Fig. 9b after consecutive slots had been machined. This may be due to slight variations between measurements and the possible attachment of material to the edge radius.

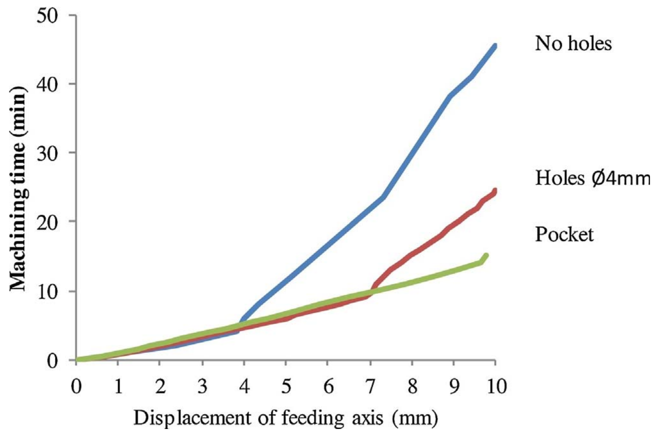

Fig. 10. Comparison of the displacement of feeding axis vs. machining time with three different electrode designs.

3.4. Lateral wear of electrode

During machining, the discharges were concentrated in the bottom area of the electrode. However, some discharges also occurred on its lateral surfaces, causing concavity to appear in the wear pattern of the electrode. These discharges reduce the width of the electrode, which can be observed near to the discharge area. In order to analyze this effect, the electrode lateral wear was measured after the machining of the set of 5 slots in the cases of machining with the conventional electrode, with the electrode with 2 mm diameter holes, and with the electrode of 4 mm diameter holes.

Fig. 11 shows the results obtained, together with an image depicting the wear pattern in a conventional electrode. The results show that the lateral wear only occurred at the tip. At 0.5 mm from the electrode tip the reduction of the electrode was 0.187 mm and when holes were used this reduction was 0.03 mm and 0.132 mm respectively.

It can be concluded that the concavity effect can be improved by flushing holes, whilst no firm conclusions can be drawn with respect to the various electrode designs.

3.5. Optimum electrode combination

As already discussed (see Figs. 8 and 10), as the machining depth increases, accumulation of debris increases, and if an electrode without holes is used the process loses stability and the machining time starts to increase.

In previous sections it was concluded that machining stability can be guaranteed when the flushing pockets penetrate the whole depth of the slot to be machined on the electrode, which in turn results in considerable improvements in machining time.

Therefore, in order to understand the machining phenomena at greater depths, two extra experiments were conducted using an electrode with flushing pockets: at a machining depth of 15 mm and at a machining depth of 25 mm.

Fig. 12 compares the average machining time and standard deviation at various machining depths. The results indicate that flushing pockets are also effective even at very high machining depths. Results show that a slight decrease of material removal rate is observed after the machining of 10 mm depth slot. Variations of removal rate when the depth increases (for instance, the slight speed increase after 15 mm) are too small to be considered since they are within the limits of repeatability of the experiment. Hence, the machining stability can be guaranteed at high depths.

It is likely that this improved stability comes from the fact that debris removal from the working gap is much more successful when pockets are machined on the electrode. In order to confirm this possibility, an analysis of process signals is presented in the next section.

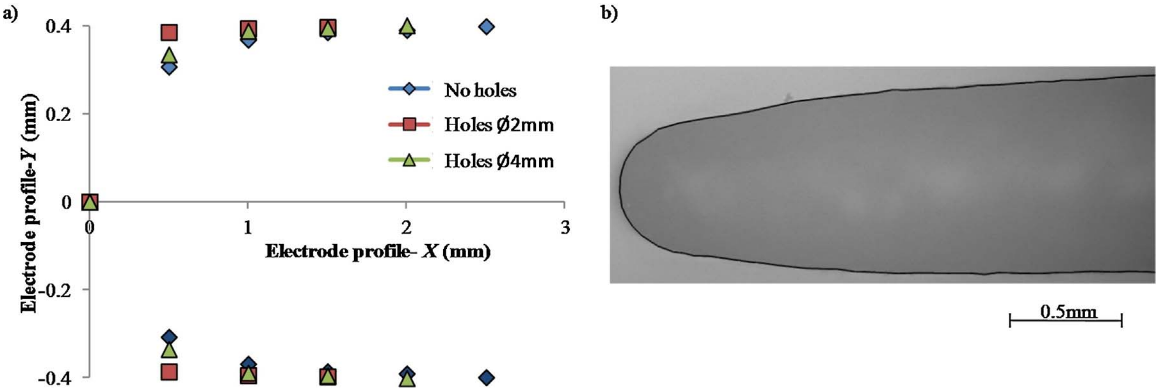

Fig. 11. Example of electrode lateral wear for a machining depth of 6.5 mm. a) Electrode lateral wear for the different electrodes b) Microphotograph of worn electrode (Conventional, No holes).

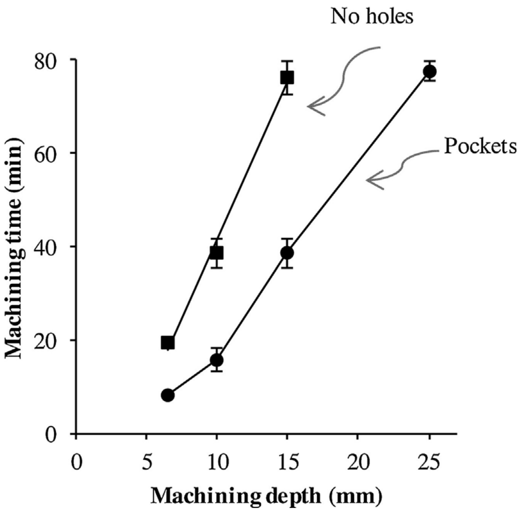

Fig. 12. Improvement in machining time at different depths using the electrode with flushing pockets.

4. Analysis of discharges in the working gap

In order to understand the reason for the improvement in machining time with an electrode with flushing pockets, a basic analysis of process parameters was carried out. A high-frequency oscilloscope (DPO 5034B Digital Phosphor Oscilloscope, Tektronix Inc.) was used for obtaining the waveforms of current and voltage during machining. The current signal was obtained using a CWT Rogowski Current Transducers (Power Electronic Measurement Ltd.), and the voltage signal was obtained by employing a High Voltage differential probe (Tektronix Inc.). The sampling rate was 1 MHz and the recording time was 4 s.

In the present study, the same machining parameters (as shown in Table 1) have been used. The machining conditions recorded are those presented in Fig. 13.

As explained in Section 2, the generator of the sinking EDM machine tool used in the experiments is an iso-energetic generator, fitted with an adaptive control that avoids inefficient discharges by controlling off-time value. In the present work, the machining performance was analyzed through a quantitative study of the main discharge parameters: duty cycle, discharge frequency, discharge delay time, and pulse off-time.

The duty cycle refers to the ratio between the total discharge time ($\sum t_{on}$) and the total recording time, which was 4 s. In order to eliminate any possible noise generated during acquisition of the signal, a discharge is deemed to have occurred when the discharge current is higher than 30 A and discharge time higher than 50 µs. The results are shown in Fig. 14.

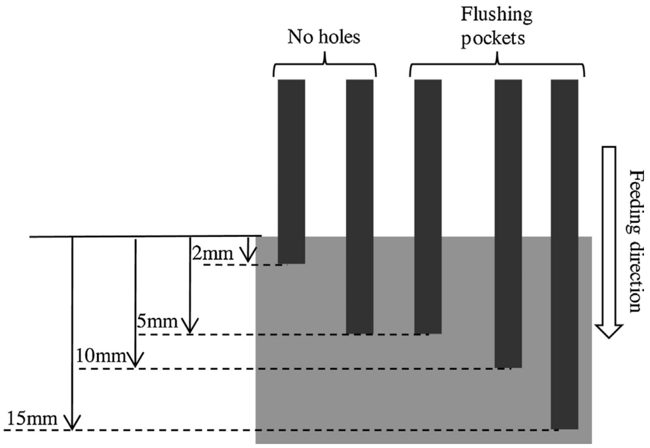

Fig. 13. Machining conditions in which machining parameters were recorded.

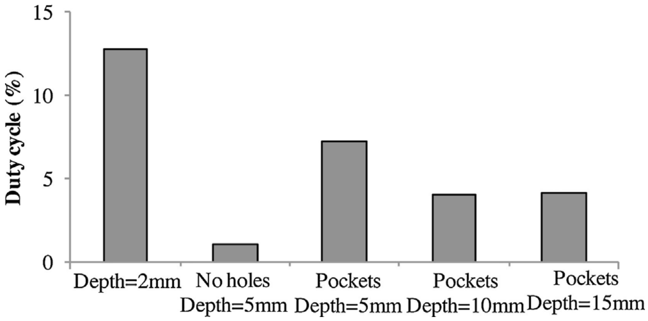

Fig. 14. Effect of flushing holes on duty cycle (%) at different machining depths.

A higher machining rate indicates a more stable, and hence, more efficient machining process, which can also be defined as better flushing conditions in the narrow gap. As shown in Fig. 14, at the beginning of the machining process, at a machining depth of 2 mm, the process is stable as there is no debris accumulation problem. However, with an increasing machining depth, at 5 mm for instance, the difference between the electrode without holes and with flushing pockets becomes clear. Even when machining deeper slots (10 mm and 15 mm), the machining time ratio is kept at acceptable values if compared with that of a conventional electrode at 5 mm depth. It must be explained here that experiments with the conventional electrode (no holes) were also carried out at 10 mm depth. However, the EDM process becomes completely unstable. For this reason it was decided not to plot these results.

In terms of discharge frequency, two outputs were analyzed, as shown in Fig. 15: average frequency and frequency during machining.

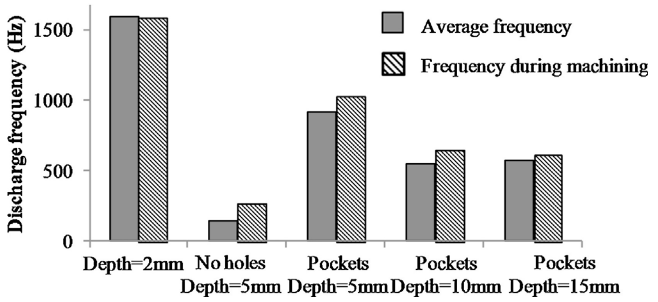

Fig. 15. Effect of flushing holes on discharge frequency at different machining depths.

The former refers to discharge frequency, which takes into account the recording of the machining time by the oscilloscope, whilst in the latter the time at which the electrode is retracted by the generator is not considered. The results show that at the beginning of each operation, in which the flushing conditions were optimum, there was no retraction of the electrode. However, as the machining progresses, retraction of the electrode occurs. Moreover, the discharge frequency results also confirm the improvement in machining conditions when using an electrode with flushing pockets.

Furthermore, as explained in Section 2, the machine generator adapts the preset value of discharge off-time in order to avoid inefficient sparks (such as arc and short-circuits), the decrease of discharge frequency when no holes are used can be used as indicator of machining instability.

A further discharge parameter that provides useful information about machining stability is the discharge delay time (t_d). It refers to the time interval between the application of voltage and the dielectric breakdown and it is affected by debris concentration, gap width, discharge area, and surface profile [15–17].

Fig. 16 compares t_d values in the five situations. In the analysis of the data, a discharge is assumed to occur if the voltage reaches 100 V and the discharge delay time is longer than 2 µs. Fig. 16a. represents the percentage of discharges classified by the duration of discharge delay time. Values of discharge delay time have been represented only up to 1000 µs. This is the reason why the summation of percentages for the conventional electrode does not reach 100%. In order to understand this effect, Fig. 16b. supports this statement. Results show that most of the discharges for the conventional electrode exhibit delay time well over 1000 µs.

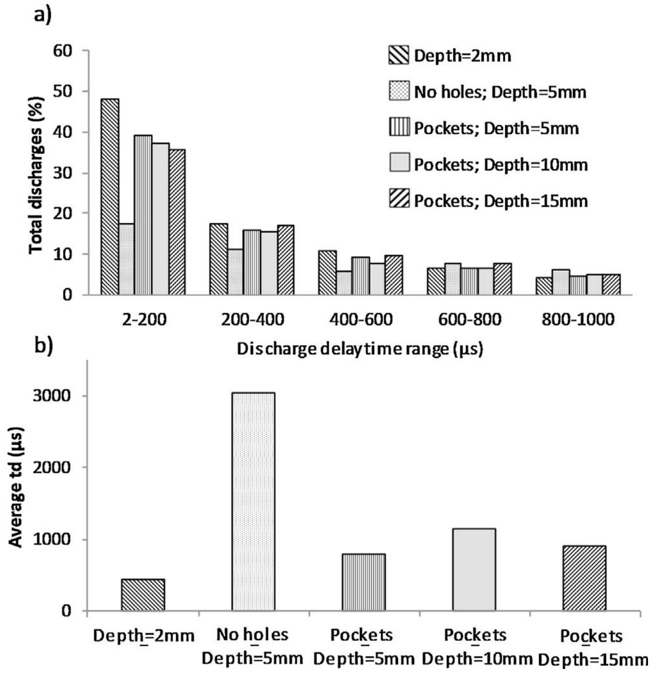

Fig. 16. Discharge delay time at different machining depths for the different electrode geometries. a) Percentage of total discharges (up to 1000 ms); b) average values.

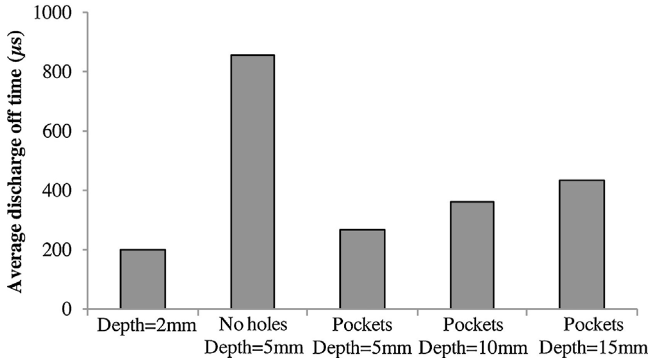

Fig. 17. Average value of discharge off-time at different machining depths.

Results of the early stage of machining, at a depth of 2 mm show that the clear majority of discharges are generated with a delay time between 2 µs–200 µs and then the percentage decreases. A clear situation of unstable machining is represented by the electrode with no holes at a machining depth of 5 mm. In this case a uniform pattern of the percentage of t_d is observed as well as a much higher value of average t_d. The longer t_d values during unstable machining are related with the longer time for the recovery of the dielectric breakdown strength, as shown in Fig. 17.

When flushing pockets are used, even though longer t_d values are observed, results show similar behavior compared with the early stage of machining. The similarities between them indicate that stable machining can be achieved even at high machining depths with the right choice of holes on the electrode.

Fig. 17 shows the average values of discharge off time (t_{off}) obtained for each machining case studied.

From Figs. 16 and 17 it can be concluded that when using an optimum configuration of flushing pockets, the values of discharge delay time and discharge off-time show similar patterns. Also, it is particularly relevant that, using the information provided by the above experiments, machining depth becomes not a limitation when the optimum configuration of pockets is arranged on the lateral faces of the electrode.

5. Conclusions

The most important and original findings of the present work are related to the geometry and the position of the holes machined on the electrode lateral faces for efficient flushing in slot EDM'ing. A remarkable and original finding is that continuous pockets or open holes are much better than the separated or closed holes. Furthermore, the paper shows that a sudden change in material removal rate occurs when the vacant spaces of the holes are sunk in the slot. This new contribution can be applied in both aerospace and dye and mold industries.

On the basis of the current findings, the following conclusions are drawn:

- Through the machining of holes of 4 mm in diameter in the electrode, a reduction of 57% in machining time is achievable when EDM machining a high-aspect ratio slot of 6.5 mm due to the chip pocketing effect of holes. Moreover, a reduction in the loss of electrode length is possible.
- When machining 10 mm depth slots, the process time can be reduced by 65% when an electrode with pockets is used. This is because the process does not lose stability along the machining depth.
- In terms of electrode wear, it was concluded that machining time is

the predominant factor in terms of loss of electrode length, whilst no firm conclusions can be drawn with respect to electrode radius edge and lateral wear.
- Machining stability can be guaranteed if the flushing pockets machined on the electrode penetrate the entire machining depth. This was confirmed by the machining of a 25 mm depth slot.
- Higher discharge frequency, duty cycle, and shorter discharge delay time and discharge off time values were observed when using the electrode with pockets. This is compatible with the experimental results.
- No marked differences in terms of discharge properties were observed between machining depths of 10 mm and 15 mm, which indicates that, in terms of process stability, flushing pockets are effective at any machining depth.
- Future work will focus on how these findings can be applied to other electrode geometries in which debris evacuation is difficult.

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