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Experimental Investigation on the Effects of the Geometry of Micro Hole on the EDM Drilling Process

Giuseppe Pellegrini (0000-0001-5138-3193), Chiara Ravasio (0000-0001-9812-7226)
University of Bergamo – Department of Management, Information and Production Engineering – viale Marconi, 5 - 24044 Dalmine (BG) – Italy

In the last years, the interest in micromachining has grown significantly due to the miniaturization of several components used in several fields such as automotive, aerospace and biomedical. In this scenario, the main protagonists are the microtechnologies and their capabilities. Micro EDM is a technology able to remove material from conductive workpieces through electrical sparks. Each spark makes a crater on the workpiece surface. Micro drilling is one of its common applications. In micro EDM drilling the geometrical characteristics of the hole are related to the electrode size. In this paper, the effects of the geometry of micro hole on the micro EDM drilling process performance have been investigated. In order to do this, experimental tests were conducted varying the electrode diameter and the aspect ratio of the hole. The influence of the electrode diameter and the aspect ratio on several indexes about process performance were established. This study contributes to improve the knowledge of the process and can support the users to establish the effects of the geometry of the hole on the machining performance.

Keywords: micro-EDM, micro drilling, performance evaluation, electrode diameter, aspect ratio

1 Introduction

During the last few years, the need to produce components of very small dimensions has produced a remarkable growth of microtechnologies, that is technologies able to carry out the processing of particulars having dimensions ranging from hundredths to a few millimeters. In this scenario, numerous researches have been conducted on microtechnologies with the aim of improving their performance [1].

Micro EDM is an unconventional technology able to remove material from a conductive workpiece. The process uses thermal energy to either melt or vaporize the workpiece material through electrical sparks between tool electrode and the workpiece, that is submerged in a dielectric fluid. During the process, the material is removed from the tool electrode too. In this case, it is named wear. The most important applications of micro EDM are drilling and milling. As regards drilling, several sectors are interested by this technology such as biomedical, automotive, aerospace and in general micro mechanical. The main advantages of micro EDM are precision, ability to realize micro holes with high aspect ratio and limited diameter (having a dimension up to some tens of micrometres); moreover, EDM is not affected by the mechanical properties of the machined parts.

The effects of the process parameters on the performance of the drilling process is widely studied in the literature. First of all, it is useful to give a clear definition of performance. There are some indexes such as MRR (Material Removal Rate), TW (tool wear), TWR (Tool Wear Ratio) that are generally used to evaluate the efficiency of the machining. Moreover, shape characteristics of the holes may be described in terms of DOC (diametral overcut) and TR (taper rate). The micro-geometrical characterization can be made through the roughness index. Anyway, this last index is not always simple to measure. Destructive methods, such as metallographic sectioning, or special purpose microscopes (such as variable focus, interferometric etc.) can be used.

Among the main control parameters in EDM, peak current, voltage, pulse on time and frequency have relevant effects [2, 3]. In [4] the authors found that peak current and pulse on time are the most important parameters affecting the machining performance. The process is also influenced by the electrode material, its rotation speed and duty factor [5, 6]. In [7] the discharge energy was introduced as parameter that determines the efficiency of the machining.

Not only the electrical process parameters affect the efficiency of the process but also the type of electrode used in terms of material and geometry (cylinder, tubular, multi-channel) [8, 9]. Last, but not least, the type of the dielectric and the workpiece material. As regards the type of dielectric, water and mineral oil are commonly used [10, 11]. In general, water guarantees better performance than oil despite of the accuracy of the machining. The properties of the workpiece material can influence the machining especially the density, the thermal conductivity and the electrical resistivity [12-15].

As far as the hole geometry is concerned, literature is not as abundant as it is about the above mentioned parameters. The main geometrical characteristic of a hole is its diameter that is controlled through the electrode diameter. In [16] the effects of the electrode size on the performances are studied. It was found that increasing the tool diameter, leads to an increase of MRR, TW, TWR and TR. Several physical phenomena, related to the electrode diameter, are presented as possible reasons of this trend, namely the skin effect, the parasitic capacitance and the debris concentration. Similar trends are also reported in [17]. However, the authors found a maximum for TWR when the electrode diameter is 500 μm. It should be noted that in [16] the range of diameters was limited to this size while in [17] the maximum diameter was 800 μm. The DOC was investigated as well finding a moderate increase with the electrode diameter possibly due to higher probability of secondary discharges.

In [18], the geometrical characterization was made considering only the surface roughness. It was found that the roughness decreases as the electrode diameter increases. Skin effect and chemical corrosion are reported as the main causes.

Opposite results were found in [17] dealing with large tools (14 and 20 mm as diameter). It was considered material removal rate, tool wear rate and surface roughness. All these characteristics slightly decrease as the electrode diameter increases.

Literature review showed that there is the need of further investigation. The objective of the present paper is to supply further information on the effects of the hole geometry on process performance. In particular, the effects of the electrode diameter and the aspect ratio on the drilling performance of titanium sheets were investigated.

Titanium applications have been spreading into many areas such as biomedical, areospace, chemical facilities, ships for marine transport (re-sistance to acids and salts), wall hooks for climbers (low density and high rigidity) due to its specific qualities. However, it is considered difficult to cut with conventional technologies while EDM is able to machine easily this material [19].

The electrode diameter varies in the range 0.05 mm and 0.3 mm while the aspect ratio in the range 3.33 - 20. The process performance were evaluated considering the MRR and the TWR. As geometrical indicators, DOC and TR were calculated. Moreover, regressive models were estimated and the analysis of the regressive coefficients and the corresponding p-values gave a measure of their significance.

2 Description of the experimental plan

A micro EDM system (Sarix SX-200) was used to machine the micro holes. Kerosene was used as dielectric fluid. Tubular tungsten carbide electrodes of different diameters were used in most cases. The smallest electrode having 50μm as diameter was cylindrical being the only geometry available on the market. Through micro holes were obtained on titanium (Ti6Al4V) specimens that were obtained from the same sheet to grant the same metallurgical conditions. Different sheets thicknesses were achieved by milling. The drilling process was made in automatic way using a program that was implemented into the EDM machine. The program records the machining time for each hole. Moreover, at the end of each hole, the clamp moves to a reference point and by an electrode touching operation, the frontal electrode wear is measured as the difference between the initial and final length of the electrode. The geometrical characterization of the micro holes was made by the measurement of both the top and bottom diameter by a microscope.

Tab. 1 reports the tested experimental conditions in terms of depth of the hole (H) and electrode diameter (Dext and Dint).

The experiments were planned following two criteria:

- The ratio between the thickness of the specimen and the electrode diameter was fixed to 5
- The thickness of the specimen was fixed to 1mm and the electrode diameter was varied

***Tab. 1** Experimental plan*

H [mm]	*Electrode*	*D_{ext} [mm]*	*D_{int} [mm]*
1.5	Tubular	0.3	0.12
0.75	Tubular	0.15	0.06
0.5	Tubular	0.1	0.04
0.25	Cylindrical	0.05	-
1	Tubular	0.3	0.12
1	Tubular	0.15	0.06
1	Tubular	0.1	0.04

It was decided to adopt the same finishing process parameters for all the tested conditions except for the smallest electrode diameter (50 μm). In fact, in this last case, the electrode is not tubular and therefore the internal washing cannot occur. The process parameters are reported in Tab. 2. As reported in Tab. 2, some parameters are set as indexes as specified by the machine constructor. The number of repetitions of each experimental condition was 10.

***Tab. 2** Process parameters*

	Tubular electrode	*Cylindrical electrode*
Polarity	-	-
Width [μs]	2	2
Frequency [kHz]	150	180
Current [index]	40	100
Voltage [V]	120	120
Gain [index]	20	10
Gap [%]	80	40
Energy	105	100
Regulation	03-01	00-00
Flushing pressure [bar]	30 / 90*	-
Spindle rotational speed [rpm]	520	520

* 90 bar only for 0.1 mm electrode diameter

The experimental plan was defined with the aim of comparing different hole geometries. Anyway, some potential problems may arise. First, the optimal electrical parameters are in general a function of the electrode diameter; in this paper all experiments were conducted using the same process parameters (see Tab. 1) to eliminate extra variables. This choice could be a source of bias for some conditions but the optimal parameters suggested by the machine constructor are very similar to each other.

Second, the electrode geometrical properties could affect its drilling performance. When testing different electrode diameters, this effect is a potential source of data scatter. In particular, in the present case, the smallest tubular electrode performed poorly using 30 bar as flushing pressure, possibly because of a partial obstruction of the electrode hole. In this case, it was necessary to increase this parameter at 90 bar. Moreover, the actual shape of the tool tip is affected by the tool wear and wear patterns depend on the depth and diameter of the hole; so systematic differences in the experimental output are to be expected.

3 Results

As mentioned above, for each experiment machining time, tool wear and the diameters of the hole were directly measured. Basing on these data, MRR (Material Removal Rate), TWR (Tool Wear Ratio), DOC (diametral overcut) and T (taper) were evaluated. MRR was calculated considering the effective hole geometry assuming to be a cone frustum. TWR is the ratio between the tool volume loss and the hole volume. DOC was calculated as the difference between the hole top diameter and the electrode diameter while T as the ratio between the diameter difference (top and bottom) and the hole depth.

The data reported in the following figures are computed as the average of the ten repetitions for each tested condition.

Fig. 1-4 shows the effects of the electrode diameter on the process performance. Fig. 1 describes the trend of the MRR. When increasing the hole diameter, MRR improves according to the literature [16]. A general regression analysis was made using Minitab software. The selected regressive model was:

$$V = a + b \cdot D_{ext} + c \cdot (H/D_{ext}) \quad (1)$$

Where:

V…The response variable, in this case MRR,

a, b, c…The regressive coefficients,

D_{ext}…The external diameter of the electrode expressed in [mm].

Tab. 3 shows the regressive coefficients and the corresponding p-values, a measure of their significance. The positive correlation with the electrode diameter (D_{ext}) is confirmed as seen in Fig. 1. Concerning the aspect ratio H/D_{ext}, the correlation is negative and significant, although it affects the response MRR less than D_{ext} does. As expected, deeper holes cause a decrease of the efficiency of the material removal process. This behaviour can be explained by considering that the debris evacuation is more difficult when the depth increases.

***Tab. 3** Regressive coefficients and p-values of MRR model*

	Coefficient	p-value
a	0.0000193	0.000
b	0.0000893	0.000
c	-0.0000005	0.021

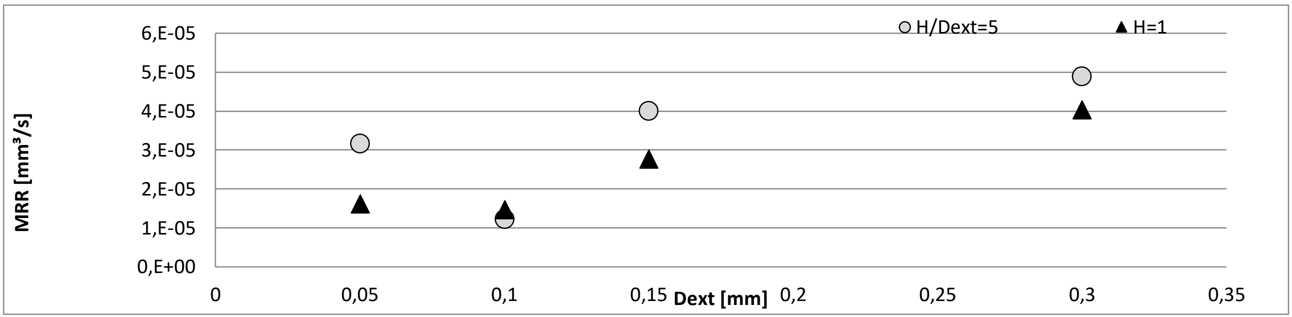

***Fig. 1** MRR as a function of the external electrode diameter*

Fig. 2 shows the TWR as a function of the hole diameter. In this case, TWR depends mostly on hole aspect ratio (H/D_{ext}). In fact, the campaign having H/D_{ext} constant does not show significant difference while increase of the diameter with constant depth shows an appreciable negative correlation. The same remarks made for MRR hold also for this case. Note that unlike for MRR, low values of TWR are preferred. The regressive model coefficients are reported in Tab. 4. Both D and H/D_{ext} are significant although in this case the effect of D_{ext} is less clear (see its p-value).

***Tab. 4** Regressive coefficients and p-values of TWR model*

	Coefficient	p-value
a	0.285981	0.000
b	-0.125329	0.085
c	0.015538	0.000

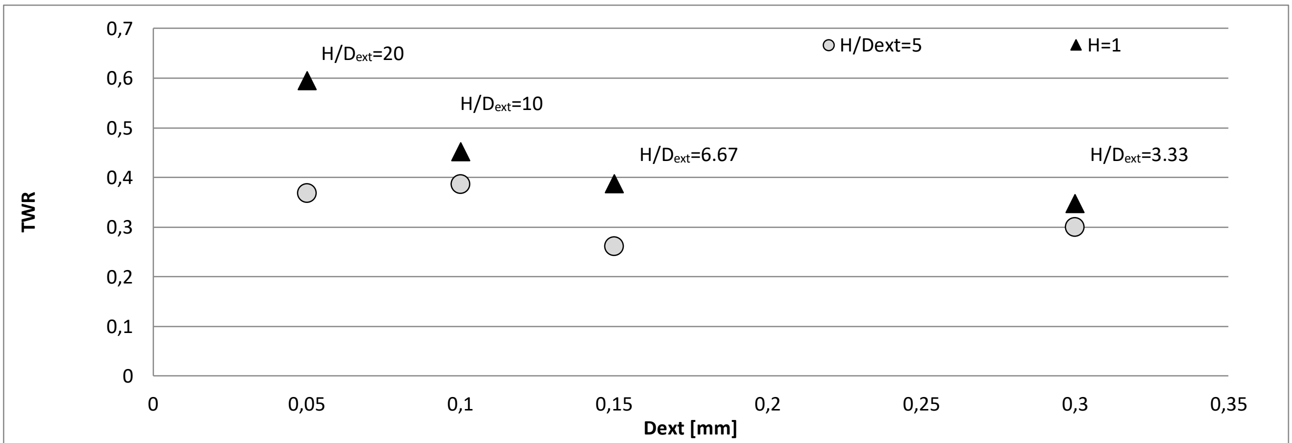

***Fig. 2** TWR as a function of the external electrode diameter*

Fig. 3 shows the trend of DOC as a function of the electrode diameter. Also in this case, DOC seems to be dependent on the electrode diameter. It should be remarked however that the biggest value is obtained with the 50 μm electrode that, unlike all the others, is not tubular. Anyway, even neglecting the 50 μm data, the difference in DOC is appreciable. The average DOC for 0.1 electrode is 33 μm and for 0.3 μm electrode is 26 μm corresponding to a decrease of 21%.

In Tab. 5, the regressive coefficients and relative p-values are reported. It can be noted that H/D_{ext} is significant on DOC but its effect is lower than that one of D_{ext}.

Both D_{ext} and H/D_{ext} influence DOC in the same way as they do on MRR and TWR. In addition, the flectional stiffness of the electrode may play a not negligible role on the DOC. Both larger diameters and shorter overhangs (the length of the electrode out of the spindle) increase electrode stiffness. In these cases, the overcut is reduced.

***Tab. 5** Regressive coefficients and p-values of DOC model*

	Coefficient	p-value
a	25.3384	0.000
b	-25.5430	0.000
c	1.5552	0.000

Fig. 3 *DOC as a function of the external electrode diameter*

Finally, Fig. 4 shows the trend of TR as a function of the electrode diameter. In this case, data are more difficult to understand. This behaviour may be due to issues in experiment control. The actual shape of the worn electrode and its position at the end of the operation depend on the process conditions (D_{ext} and H/D_{ext}) in a way that is difficult to predict. A rather poor correlation between TR data were found so statistical data will not be further discussed here. A thorough study of TR should include a careful control of tool wear and other geometrical process parameters.

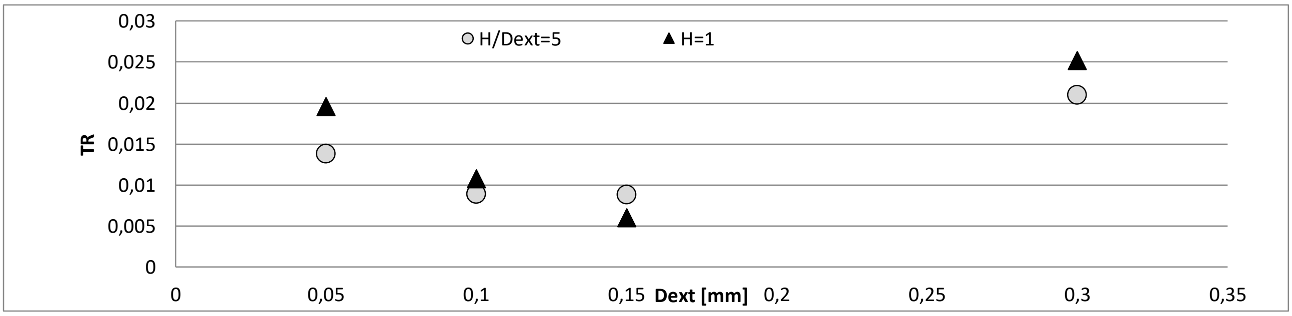

Fig. 4 *TR as a function of the external electrode diameter*

4 Conclusion

The effects of the geometrical characteristics of the micro-EDM hole on the process performance were investigated. In particular, electrode diameter and hole aspect ratio were varied. It was found that both variables significantly influence the drilling operation.

As regards the electrode diameter, it affects significantly the MRR and only slightly the others performance indexes. Aspect ratio impacts almost all the process performance; anyway none of these effects has the same extent as the electrode diameter on MRR.

In general, the miniaturization of holes involves more difficulties: MRR decreases, TWR increases and also DOC is larger.

This behaviour can be explained considering the different concentration of debris. Larger holes involve a higher level of contamination besides contamination increases as long as the drilling process evolves: the debris removal from the bottom of the hole is more and more difficult as the operation is carried on. This behaviour justifies the effects of the aspect ratio on most performance indexes.

Moreover, it was observed that the feed rate during the drilling operation varies over time as the debris concentration does. The study of process evolution may give a contribution in understanding the effects of debris concentration on EDM performance.

References

[1] PODANY', J., TOMICEK, J. (2020). Analysis of small holes manufacturing for optomechanical components. In: *Manufacturing Technology* Vol.20(2), pp. 229-236

[2] SONA, S.M., LIMB, H.S., KUMARB, A.S., RAHMANB, M. (2007). Influences of pulsed power condition on the machining properties in micro EDM. In: *Journal of Material Processing Technology*, Vol. 190, pp. 73–76

[3] DENKENA, B., HOFFMEISTER, H.W., REICHSTEIN, M., ILLENSEER, S., HLAVAC, M. (2006). Micro-machining processes for microsystem technology. In: *Microsystem Technology*, Vol. 12, pp. 659–664

[4] PRADHAN, B.B., MASANTA, M., SARKAR, B.R., BHATTACHARYYA, B. (2009). Investigation of electro-discharge micro-machining of titanium super alloy. In: *International Journal Advanced Manufacturing Technology*, Vol. 41, pp. 1094-1106

[5] D'URSO, G., RAVASIO, C. (2019). Investigation on the Effects of Exchanged Power and Electrode Properties on Micro EDM Drilling of Stainless Steel. In: *Manufacturing Technology* Vol.19(2), pp. 337-344

[6] KUPPAN, P., RAJADURAI, A., NARAYANAN, S. (2008). Influence of EDM process parameters in deep hole drilling of Inconel 718. In: *International Journal Advanced Manufacturing Technology*, Vol. 38, pp. 74-84

[7] KIYAK, M.et al. (2015). Effects of discharge energy density on wear rate and surface roughness in EDM. In: *International Journal Advanced Manufacturing Technology*, Vol. 79, pp. 513-518

[8] JAHAN, M.P., WONG, Y.S., RAHMAN, M. (2009). A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials. In: *Journal of Material Processing Technology*, Vol. 209, pp. 3956–3967

[9] YILMAZ, O.M., OKKA, A. (2010). Effect of single and multi-channel electrodes application on EDM fast hole drilling performance. In: *International Journal Advanced Manufacturing Technology*, Vol. 51, pp. 185–194

[10] ABBAS, N.M., YUSOFF, N., WAHAB, R.M. (2012). Electrical discharge machining (EDM): practises in malaysian industries and possible change towards green manufacturing. In: *Procedia Engineering*, Vol. 41, pp. 1684-1688

[11] NIAMAT, M., SARFRAZ, S., AZIZ, H., JAHANZAIB, M., SHEBAB, E., AHMAD, W., HUSSAIN, S. (2017). Effect of different dielectrics on material removal rate, electrode wear rate and microstructure in EDM. In: *Procedia CIRP Design*, 2-7

[12] FONDA, P., et al. (2008). A fundamental study on Ti-6Al-4V's thermal and electrical properties and their relation to EDM productivity. In: *Journal of Material Processing Technology*, Vol. 202, pp. 583-589

[13] MUHARDIKA, M., et al. (2008). A new approach on the determination of ease of machining by EDM processes. In: *International Journal of Machine Tool and Manufacture*, Vol. 48, pp. 746-760

[14] TSAI, Y.Y., MASUZAWA, T. (2004). An index to evaluate the wear resistance of the electrode in micro-EDM. In: *Journal of Material Processing Technology*, Vol. 149, pp. 304-309

[15] KHAN, A.A., et al. (2018). Performance of electrical discharge machining (EDM) with nickel added dielectric fluid. In: *IIUM Engineering Journal*, Vol. 19, pp. 215-222

[16] LIU, Q., et al. (2016). Effect of Electrode Size on the Performances of Micro-EDM. In: *Materials and Manufacturing Processes*, Vol. 31, pp. 391-396

[17] WANGA, K., et al. (2018). Influence of tool size on machining characteristics of micro-EDM. In: *Procedia CIRP*, Vol. 68, pp. 604-609

[18] LIU, Q., YANG, F., SUN, S., YANG, M., SHAO, J. (2019). Surface Integrity of Micro EDM Surface Using Electrodes of Various Diameters. In: *Coatings*, Vol. 9: 805

[19] VASILKO, K. (2019). Titanium and Technological Problems of Its Machining. In: *Manufacturing Technology* Vol.19(3), pp. 525-530