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INVESTIGATION ON ELECTRODE WEAR IN MICRO-EDM DRILLING

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Abstract

Micro-EDM drilling is extensively utilized in various industrial sectors due to its capability to machine all types of conductive materials, irrespective of their mechanical properties. This technology is particularly advantageous for drilling applications requiring high aspect ratios and precision. However, electrode wear, both frontal and radial, poses significant challenges, especially in blind hole drilling. This study proposes a mechanical method to measure electrode geometry through touch operations on a sharp target, varying the spindle rotation angle and Z depth. The method's effectiveness was validated through extensive experiments on Ti6Al4V plates using cylindrical and tubular electrodes of different diameters. The study varied energy types and tested new and steady-state electrodes. Results demonstrated the method's ability to detect changes in electrode tip shape under different conditions, revealing phenomena such as the correlation between electrode runout and wear, and the impact of internal washing on tip shape.

Keywords:
micro-EDM, micro drilling, electrode wear, frontal wear, axial wear, electrode shape

1 INTRODUCTION

Electrical Discharge Machining (EDM) is an unconventional technology used to remove material from electrically conductive workpiece. The material is removed through electrical discharges between the tool and the workpiece. Each discharge causes on the workpiece surface a very small crater which dimension depends on the process parameters used. However, the material is removed not only from the workpiece but also from the electrode tool causing wear. Between electrode and workpiece, a dielectric fluidi is present that permits the formation of the discharges, the restriction of plasma channel, the heat removal from workpiece and electrode and the evacuation of the removed material that resolidifies into the dielectric.

As a function of the dimension of the holes or features to realize, the process can be classified in macro or micro up to nano-EDM [Kumar 2020]. The downscale of the process introduces ever more the need to control every aspects of the process such as the debris circulation and the shape of the electrode.

In micro scale, EDM is particularly used to realize micro holes. Considering the current need of increasing the sustainability of manufacturing technologies, more attention is given on the critical aspects. First, the process is characterized by low MRR (Material Removal Rate). The optimization of the process parameters helps to increase it. Moreover, new solutions are suggested like PMEDM (Powder Mixed EDM) or Hybrid-EDM to increase the MRR. Second, the type of dielectric affects the level of the sustainability of the technology. The traditional hydrocarbon is considered the less green dielectric and can be replaced with water or unconventional dielectric like vegetable oils [Hourmand 2017]. Finally, the consumption of the electrode represents another critical aspect especially for micro applications. The electrode wear represents a consume of the tool that penalizes in general the sustainability of the technology. In micro applications, it is mandatory to monitor the electrode wear and some compensative methods must be taken into account to guarantee high accuracy in the machining. For these reasons, researchers are very interested in the study of the wear of the electrode and several papers are available in literature.

In micro applications, the estimation of the electrode wear is particularly critical considering the very small volumes [Bigot 2005]. Literature defines two types of electrode wear, such as frontal or axial and radial or corner, as a function of the involved region of the electrode itself. The entity of both wears is strictly connected to the properties of electrode material, such as thermal diffusivity [Tsai 2004]. In particular, the corner wear is more related to the thermal conducitivity, it is more evident with low thermal conductivity of the electrode material. The product between thermal conductivity and the melting point of the electrode material has been widely used as an effective measure of the wear resistance.

If the frontal wear is not taken into account, it causes poor accuracy in the planarity for micro milling applications and in the hole depth when blind micro holes are machined. The frontal wear can be easily measured by two touch operations, the first one before the machining while the second one after the machining. By the difference of these two coordinates, the electrode wear is estimated. In micro machining, when the material removed between the two touch operations is too little, the measurement could not be accurate enough [Tsai 2004, Valentincic 2021]. This method is especially suggested for large electrodes.

The measurement of the radial wear is more difficult and different methods are proposed. First, by the assumption that the internal geometry of the hole is linked to the electrode shape, information of the electrode shape are acquired by observing the hole section. In [Bigot 2005] this method was proposed and the authors found that the shape changing occurs especially in the first part of erosion depth and then the shape becomes stable. In authors' opinion, the reason is related to the electrical field that is stronger at the corners first and then at the middle part of the electrode surface. By this interpretation, the formation of the tip takes place in the first part of the machining and then the shape assumes a steady state.

Second, the radial wear can be estimated by optical methods by for example SEM images of the electrode tip This method was used in [Tsai 2004] where electrode wear has been investigated in the production of holes array. In [Hou 2022] a simulative and experimental study on the evolution of the electrode morphology in machining micro holes array was conducted. The morphology of the electrode tip is captured by a camera. As the number of the hole increases, the electrode tip changes. The results obtained by simulative and experimental method match very well. Finally, a model for compensating the electrode wear was proposed.

Finally, the volumetric electrode wear can be estimated by using a laser. In [Valentincic 2021] the authors investigated on the measurement methods of the electrode wear and the laser method revealed to be effective to acquire the electrode profile and monitor the volumetric wear of the electrode.

Several papers are available in literature on the study of the effects of the process parameters on electrode wear. Pulse duration, current and the type of the current slopes, pause duration are the most important parameters affecting the electrode wear when graphite electrode is used [Maradia 2015]. Tool wear modeling using regression analysis and artificial neural networks are reported, for frontal wear, in [Puthumana 2017]. From these results, the determination of the processing conditions to minimize the tool wear can be obtained.

An important factor affecting the electrode wear is the dielectric washing. In micro-EDM drilling, the dielectric is continuously renewed and the dielectric, flowing through the machining gap, is enriched by debris from the resolidification of removed material from both the workpiece and the electrode. The presence of debris changes the properties of the dielectric and therefore has effects on the removal process. The external washing consists of the use of a nozzle from which clean dielectric goes out. The internal one, especially useful in the case of deep hole, can be used when tubular electrodes are available. In this case, from the internal diameter of the electrode, clean dielectric at varied prerssure flows to the machining zone. It was found that the electrode type, tubular or rod electrodes, causes differences on the wear [Pham 2007]. By using tubular electrodes, the dielectric flow is more efficient in the debris evacuation and both the electrode shape and the frontal wear are almost stable. In the other case, by using rod electrodes, the washing action is less efficient and in some zone high number of debris can be accumulated causing abnormal discharges on the side of the hole. This result was confirmed in [Liu 2020]. By the assumption that dielectric flow affects the debris removal from the machining zone, simulative study showed that the flow velocity decreases when the ratio between the depth and the diameter of the hole increases. It was also found that the electrode tip tends to be stable when the number of machined holes is sufficient while the axial wear is proportional to the number of the holes [Liu 2020, Liu 2022].

The important effect of the debris in the tool wear evolution was confirmed in [Zou 2023] as well where authors proposed an innovative method to minimize the uneven tool wear by alternating the polarity during the machining.

Another aspect that should be taken into account is related the eddy current generated by the varying electromagnetic field in time under high fluctuation frequency of discharge current. The eddy current modifies the current density on the electrode surface and consequently the electrode topography [Li 2014].

In milling applications, the electrode wear was demonstrated to be linked to the trajectory and electrode profile [Jacques 2018]. For cylindrical electrodes, when the trajectory occurs in full material the electrode profile shape becomes conical while with a zigzag trajectory it becomes more complex but connected with the tool-path overlap. EDM gap affects the electrode's profile especially for micro electrodes and as the gap increases, the electrode profile tends to be cylindrical.

The prediction of the volumetric wear is complex in micro applications considering that some variations, negligible in the case of macro, affect the erosion process [Ivanov 2007]. The small variations are related to the sparking conditions, such as dielectric temperature, purity of both workpiece and electrode material, spark energy and so on. Therefore, the accuracy of machining is influenced by the accuracy of the compensation method used and finally by the accuracy of the wear estimation.

The evolution of the shape of the electrode tip was studied in [Li 2014]. It was found that it tended to a stable elliptical model. Moreover, when the number of machined holes is sufficient, the electrode axial wear tends to be uniform, indicating that a compensation method can be easily implemented.

The entity of frontal electrode wear is affected by the power modes, the voltage, the capacitance and also by the workpiece thickness and electrode diameter [Hou 2020]. The authors observed that as the number of holes increases, the shape of the electrode bottom becomes stable but the taper angle at the bottom of the electrode increases due to the side wear caused by accumulated debris and secondary discharges. The length of axial wear depends on the hole depth.

The problem of the electrode wear can be solved using strategies like the real time monitoring of the electrode through the study of some electrical signals followed by compensation methods [Nguyen 2015]. This method improves the accuracy of the machining. A similar approach was tested in [Bissacco 2010]. Basing on discharge counting and the estimation of materials removed from anode and cathode, both electrode wear and material removal per discharge were measured. However, the authors declared that the measurement of the eroded material is subjected to high errors considering the small volumes and the high roughness on the surfaces especially for electrode. The electrode wear was measured by touching a reference point before and after machining. They concluded that the real-time wear sensing method for electrode wear compensation cannot be considered an effective method.

Another strategy consists of a vision system for the electrode to measure both front and corner wear [Yan 2009]. The comparison between the estimated size of the tool and the results using a microscope was about of 3% and was tested for micro drilling and micro milling applications. The combination of two techniques, the linear compensation method (LCM) and the uniform wear method (UWM), was proposed and valuated in [Yu 2010] by machining square cavities. The method was also implemented in a CAD/CAM system.

A method based on the scanned area in micro-EDM milling was proposed in [Li 2013] and compared with other compensation methods. The scanned area method consists of the slicement of a cavity into layers of the same thickness and the calculation of the area of each layer. The electrode axial feed is then calculated basing on the layer thickness and the electrode wear length. The performance in terms of MRR (Material Removal Rate) and TWR (Tool Wear Ratio) was improved with respect to the traditional compensation methods.

In this paper, a method to measure the radial wear of the electrode tip was presented. The method consists of radial touch operations of the electrode varying both the axial Z position and the rotation angle. Different tests were conducted to validate the accuracy of the method. Micro holes on titanium alloy varying the eltrode diameter, the starting condition of the electrode, the type of dielectric washing, the discharge energy level and the hole depth were made. This method revealed to be efficient in monitoring the electrode shape and to study the effects of the operative conditions on the change of the electrode tip.

2 MEASUREMENT METHOD OF THE RADIAL ELECTRODE WEAR

A radial touch operation was set to measure the shape of the electrode tip after the machining. It exploits a feature available on most EDM devices, consisting in moving a machine axis until a short circuit is detected. Considering the very small electrode dimension in micro drilling, the touch of the electrode is made against a very sharp piece, in this case a shaving blade (see Fig. 1). The touch operation consists of the following steps:

- the electrode is positioned in proximity of the touch point with a null angle rotation (C axis);
- the Z-position (axial) of the measurement is set;
- a touch operation follows.

The procedure was repeated varying the rotation angle (step of 10°) for each Z position. From the tip of the electrode, the measurement depths were: 0.01, 0.015, 0.02, 0.025, 0.03, 0.05, 0.07, 0.09, 0.15, 0.25, 0.35, 1, 1.5mm.

Each measurement cycle was repeated three times to verify the repeatability of the measurement, the measurement operation of each electrode takes around 40 minutes resulting in 13x36x3 coordinate touch values. The procedure was completely automatized by a program.

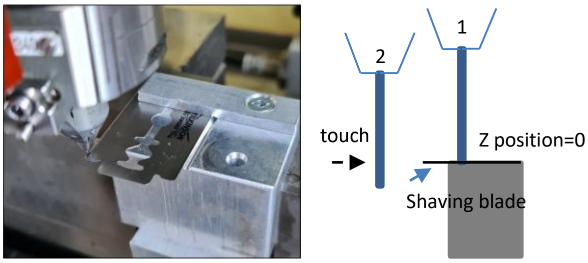

Fig. 1: Touch operation.

From the acquired data, different graphs can be obtained. Fig. 2 shows the touch coordinates as a function of the rotation angle varying the Z position; it can be noted that the electrode wear is first located at maximum runout, then radial wear erases the effect of runout and the radial measurements are independent from the angle. Fig. 3 reports the electrode touch in the XY plane varying the Z position. The black dots represent two circumferences having 0.3mm and 0.2mm as diameter. It can be noted that in proximity of the electrode tip, the radial wear has cancelled the run out while at the top, where the electrode is subjected to a negligible wear, the curves are not perfect circumferences. Fig. 4 reports the profile of the electrode in the XZ plane. For each Z position, the touch operation has been made varying the rotation angle, step of 10°. In the rotation angle where the run out is the highest, the touch point takes place before (red curves). The opposite side from this position (+180°), the run out is lowest and the touch point occurs after (green curves).

Using the whole set of data, the 3D electrode shape could be reconstructed.

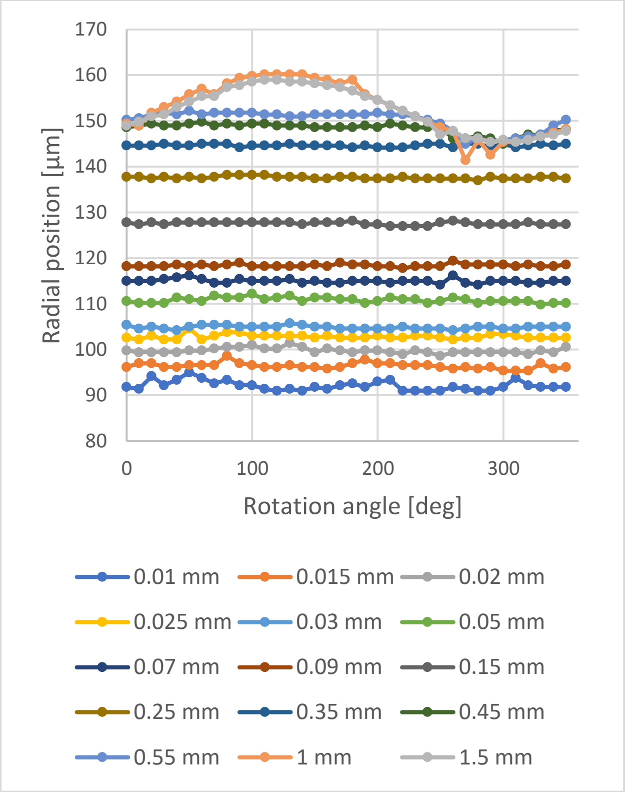

Fig. 2: Touch coordinate as a function of the rotation angle varying the Z position, cylindrical electrode.

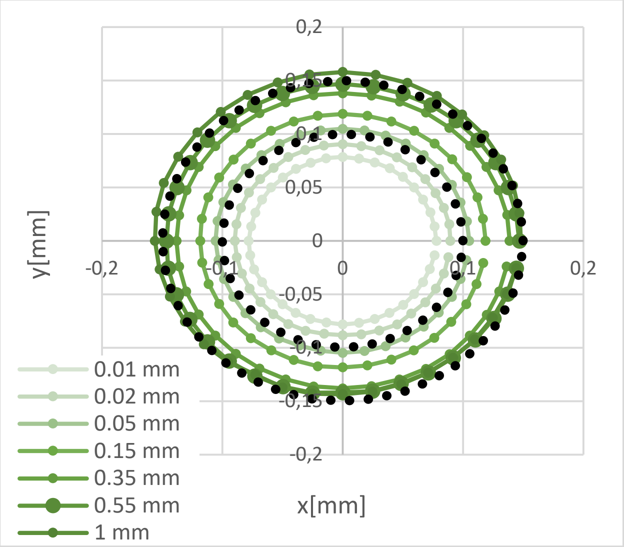

Fig. 3: Touch in the XY plane varying the Z position, cylindrical electrode.

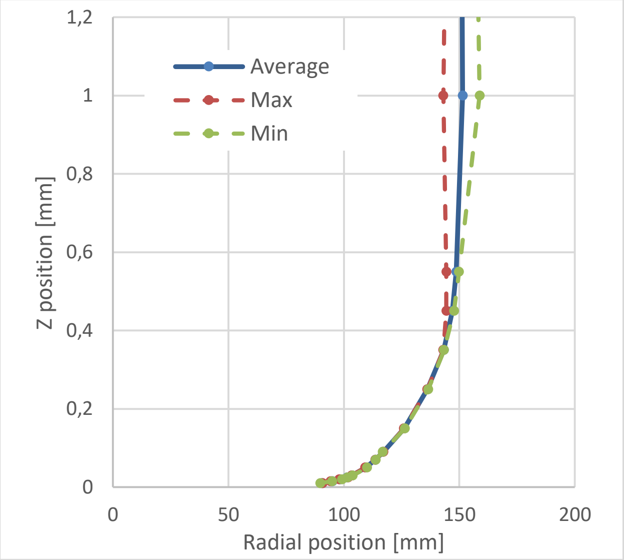

Fig. 4: Profile of the electrode in the XZ plane, cylindrical electrode.

3 EXPERIMENTAL PLAN

The experimental tests were made using the Sarix Sx-200 machine. Micro holes on Ti6Al4V plates with different depth, 1 and 2mm were machined. Tungsten carbide electrodes varying the diameter (0.1- 0.3mm) and the type (cylindrical or tubular) were used. Two different starting operative conditions were studied: by using a new electrode tip or by using an electrode having a steady state tip. Two machining parameters sets were tested, performing both a finishing operation and a roughing one.

4 ANALYSIS OF THE RESULTS

4.1 Cylindrical vs tubular electrode

A comparison between cylindrical and tubular electrode can be seen in Fig. 5, showing the steady state radial wear profiles of a 0.3 mm diameter electrode after machining holes 1 mm deep, with finishing conditions. Differences between profiles are noticeable and they may be related to different debris contamination. The cylindrical electrode is less efficient in removing debris so increasing the amount and distribution of radial wear. A larger number of debris remains in the machining zone, and the change in the dielectric characteristics made the formation of discharge easier. This phenomenon improved the MRR but also increased the electrode wear. Flushing dielectric through tubular electrode guarantees low debris contamination level and moreover it cools the electrode wear improving its integrity [Yilmaz 2010].

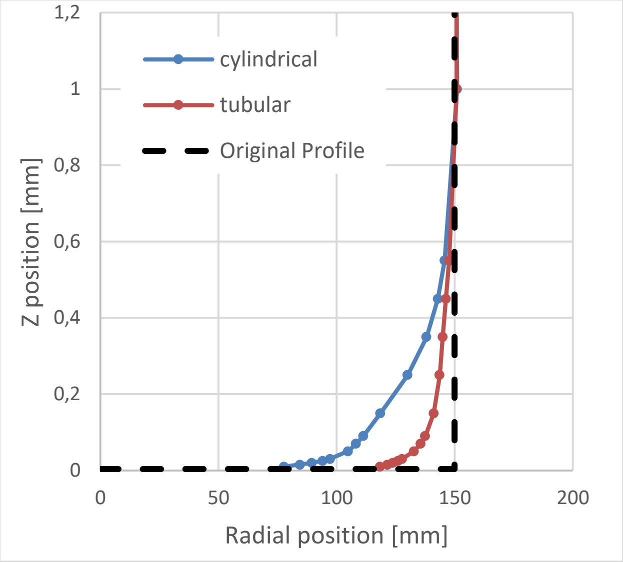

Fig. 5: Profile of cylindrical and tubular electrodes. Finishing energy, 0.3 mm, hole depth 1 mm

4.2 Effect of hole depth

Using a tubular electrode, it is possible to drill thicker sheets. A profile of a steady state worn electrode (having 0.3 mm diameter) after drilling 2 mm deep holes is shown in Fig.6, where it is compared with the profile reported in the previous figure, when 1 mm holes were machined. Deeper holes increase the radial wear of the electrode since the volume of material to be removed is larger. The axial extent of the radial wear is caused by the lateral sparks, made more likely by the debris flowing towards the top of the hole. Increasing the hole depth led to degraded flushing action and more frequent abnormal discharge that cause an increase of the electrode [Liu 2020].

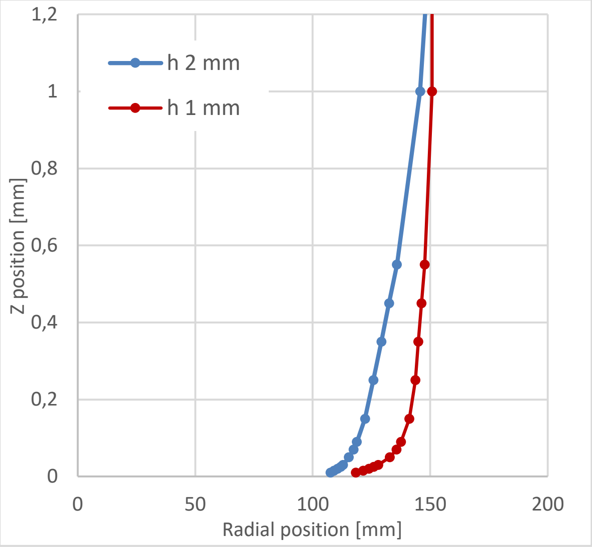

Fig. 6: Profile of tubular electrodes drilling holes of 1 and 2 mm.

4.3 Effect of electrode diameter

Fig 7a shows a comparison between profiles of cylindrical electrodes, worn after drilling holes in a specimen with thickness 1 mm. Finishing energy was set for both experiments and steady state conditions were used. The same information is displayed in Fig 7b, but in this case the ratio between actual radial size and initial electrode radius (nominal) is taken into account for sake of comparison.

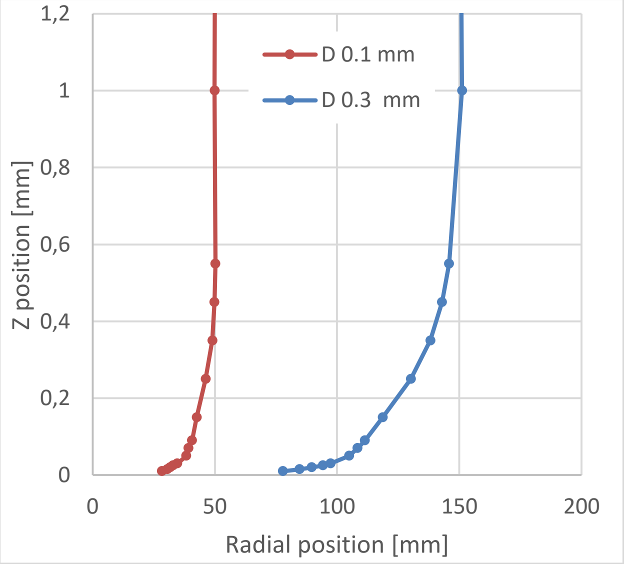

Fig. 7a: Profile of cylindrical electrodes of different sizes – actual dimensions. Finishing energy, cylindrical electrode, hole depth 1 mm

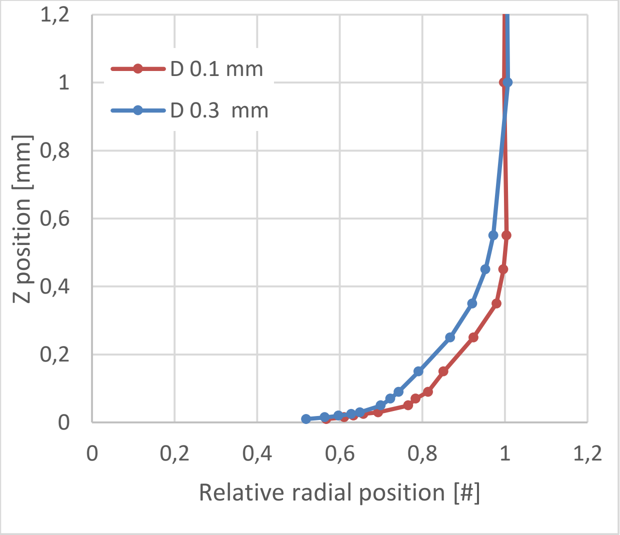

Fig. 7b: Profile of cylindrical electrodes of different sizes – radial ratio.

It is worth reporting that the diameter overcut (difference between the hole size, evaluated at the entry surface, and the electrode size) was very similar in both cases and that the material removal rate of the larger electrode proved to be about double than for the smaller one. Wear for the 0.3 mm electrode is larger, leading to a sharper electrode taper.

Because of the size effect, larger electrodes have higher concentration of debris at their bottom and this effect may explain this difference.

4.4 Effect of initial trimming

In order to evaluate the evolution of the radial profile, the electrode shape was measured after machining a single hole and after the 3rd hole, when steady state condition is likely to be reached. At the beginning of the test a perfectly cylindrical shape was achieved by WEDM (wire EDM) trimming of the electrode. Fig. 8 shows the comparison between results. This result is in agreement with the literature, the electrode tip tends to be stable when the number of machined holes is sufficient [Liu 2022].

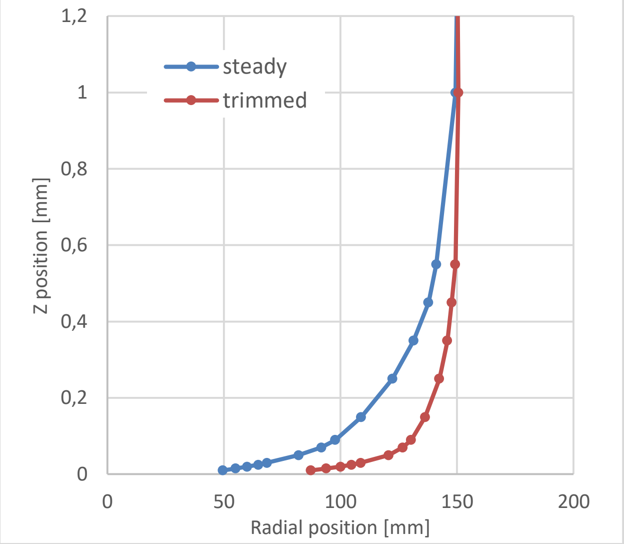

Fig. 8: Effect of electrode staring condition. Finishing energy, cylindrical electrode, 0.3 mm. Hole depth 1 mm.

4.5 Effect of spark energy

When comparing different spark energies, even if axial electrode wear may change significantly, the radial wear profiles are quite similar to each other. However, when higher energies are involved, radial wear does not erase the effect of runout. This behaviour can be seen in Fig. 9, where a constant radial position is never reached for roughing energy. Such effect could be related to a different level of debris contamination or to a larger debris size.

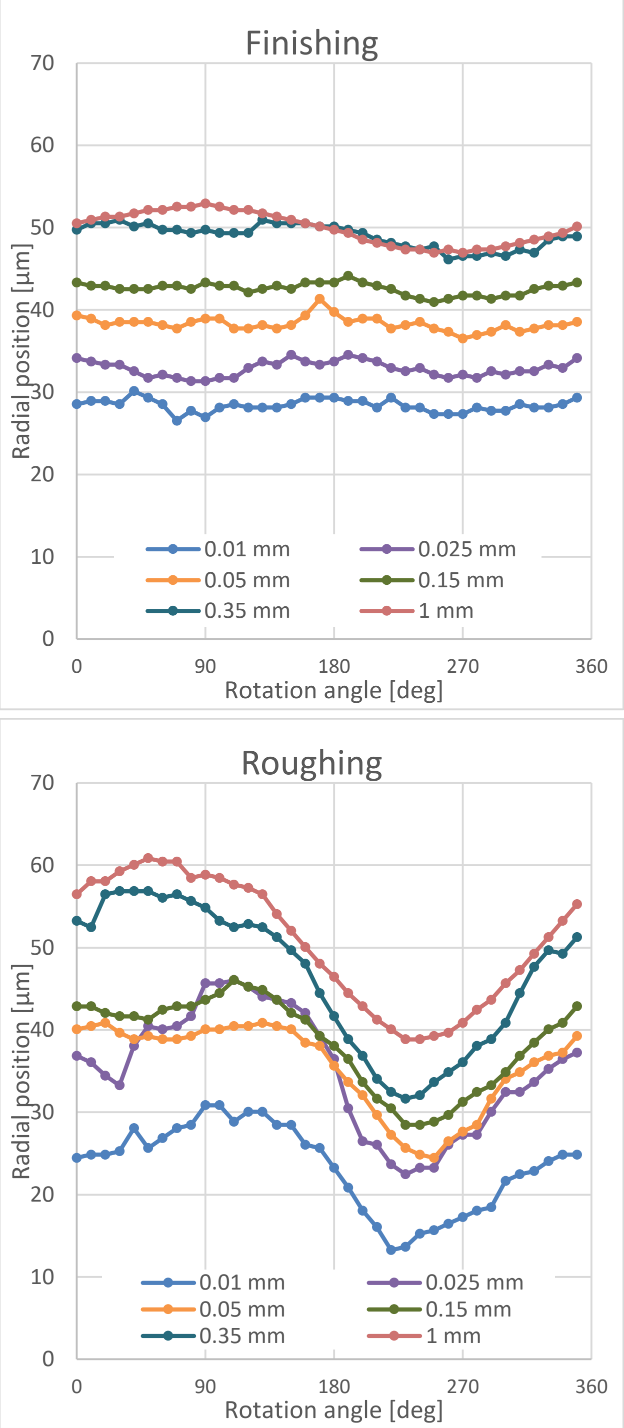

Fig. 9: Radial position vs rotation for finishing and roughing energies, cylindrical electrode, 0.1 mm. Hole depth 1 mm.

5 CONCLUSIONS

In micro-EDM drilling, it is important to monitor the shape of the electrode tip because it is strictly connected to the internal geometry of the hole.

In this work a mechanical method to measure the electrode shape in micro-EDM drilling process has been proposed. Touch based techniques yield an intrinsically numeric output, so there is no need of manual image processing. Data can be collected directly using a machine part program. The electrodes are measured while still held on the machine spindle, preserving information about the phase orientation of measurements and runout information. It is worth mentioning that this procedure does not involve cutting the electrode tip, preventing loss of electrode. The knowledge of the tip electrode shape supports process optimization.

The tested case studies confirmed the ability of the method of appreciate small differences in the electrode shape. In micro EDM drilling, operative conditions affect the removal process and, very likely, the distribution of debris at the bottom of the hole, causing a shape change of the electrode. Tubular electrodes preserve better their original shape than cylinder ones thanks to the flushing dielectric that removes debris and cools the electrode. Radial wear increases with the hole depth since the volume of material to be removed is larger. Larger electrodes are are affected by a higher radial wear due to the size effect. As the hole number increases, the electrode reaches a stable shape. The process parameters affect the removal process and also the radial wear.

Among the critical aspects of this procedure, accuracy issues should be reported, that can be minimized by repeated measurements; although repetitions increase measurement time, that is already long.

The developed method to monitor the electrode shape in drilling operation is very time consuming but in research activities could be easily implemented during the experimental campaign and the elaboration phase can be made in automatic way. Moreover, the measurement cycle can be optimized by increasing the angle step and by reducing the Z positions. It could be reduced also the repetition number only if the data accuracy will be improved.

The study of both the electrode tip during the machining and the electrode law motion into the workpiece is useful to find the best shape of the electrode to maximize the process performance.

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