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Study about the Influence of powder mixed water based fluid on micro-EDM process

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Abstract

This paper discusses the performance of micro-electro-discharge machining (micro-EDM) process using different flushing media. Several tests have been performed considering a hardened steel thin workpiece machined via micro-EDM drilling and through-trench and different flushing fluids: deionized water, tap water, deionized water with Garnet, tap water with Garnet. Garnet is the abrasive material exploited in the micro-AWJ and the concentration per liter of water considered in micro-EDM experiments is the same as required in micro-abrasive water jet (micro-AWJ) machining. A customized system has been built on micro-EDM Sarix SX 200 HP machine to allow the water-based fluid refill and liquid level monitoring during the experiments. The micro-EDM trials have been carried out considering two machining regimes, roughing and semi finishing. The different water-based fluids have different electrical conductivities, which lead to different machining performance. Material removal rate (MRR) and tool wear ratio (TWR) have been estimated in terms of average and standard deviation. The results show that the presence of Garnet does not affect MRR consistently, since the particles do not play an active role in the erosion process but affect surface quality, as proved by the inspection of crater morphology and dimensions estimation performed via confocal microscope. For the considered experiments, MRR is generally increased as the conductivity decreases, in particular when semi-finishing regime is used. Also TWR decreases dramatically with the use of water-based fluids, since a protective recast layer is also deposited on the tool tip preventing wearing. Our analysis shows that micro-EDM can be successfully performed using the same liquid (water and abrasive) used in micro-AWJ, and so paves the way towards the implementation of a hybrid process based on micro-AWJ and micro-EDM technologies.

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Keywords: Micro-EDM; Hybrid process; Micro-AWJ; Flushing fluid; Machining performance.

1. Introduction

Hybrid processes involving micro-EDM have been widely explored in literature in combination with other micro-machining technologies, such as laser beam machining [1], selective laser melting to fabricate Ti–6Al–4V micro-implantable parts [2], ultra-sonic and vibration machining and more [3]. Although hybrid processes presented in [1]-[2] can be considered more properly as sequential micro-machining (which concerns the possibility of performing two or more micro-technologies on a single machine tool at the same time [4]), a degree of technological hybridization can be still acknowledged if these technologies can share same equipment units. In this work, the study about micro-electro-discharge micro-EDM machining performed considering same fluids typically used in micro-abrasive water jet micro-AWJ is presented in the view to developing a hybrid process.

Micro-AWJ is used to machine a wide variety of materials, from tough metal alloys to polymers, from advanced ceramics to layered composites [1]. The jet, made of high speed water and mineral abrasive particles, is able to remove the material by abrasion-erosion mechanisms. The characteristic jet dimension is defined by the focusing tube exit diameter, usually ranging from 0.2 mm to 1 mm. Although the obtained surface quality may be valuable (e.g. surface roughness-Ra down to 500 nm on the solid metal wall using superfine abrasives [6]), the main issues hindering the diffusion of micro-AWJ as a near-net-shape machining system are the presence of

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intrinsic geometrical defects and the lack of dimensional accuracy on small components. Micro-EDM is generally adopted to machine micro-features on hard conductive materials [7]. Series of electrical sparks remove material from the workpiece by melting and evaporation. This technology offers the chance to accomplish high accuracy in complex 3D micro-features although it is highly time-consuming.

Combining and integrating micro-AWJ and micro-EDM can improve the efficiency and quality of the process. The first step towards such hybridization concerns the exploitation of same water-based fluids added with abrasive to be used in both technologies.

While an attempt of integration of macro AWJ and EDM has been proposed [8], very few works have been performed concerning the microscale. In [8], the authors explored the viability of performing die-sinking EDM on steel workpiece using abrasive high pressure jet. The authors highlighted the fundamental role of the flushing system in EDM, since the rise of the dielectric fluid pressure increases the metal removal rate (MRR) and reduces surface roughness. The investigation has been performed considering different fluids, such as deodorized kerosene, mineral oil and deionized water, with and without abrasive, i.e. SiC nanoparticles. The presence of nanoparticles enhances MRR of the process; this is particularly evident in the case of deionized water, increasing its value up to 8 times. Moreover, the related surface roughness values are comparable to the ones obtained with the other investigated fluids, with the exception of fine-finishing trials.

Several works in literature report results about the use of different fluids, added with powders or particles in classic EDM [9]-[10]. The focus is on the proper choice of process parameters for different alternative solutions, in order to estimate process stability, tool wear, surface quality of the features and the actual role of the powder mixed with the fluids during machining in relation to the materials involved (workpiece and tool). The use of both distilled and tap water as fluids is widely discussed in [11], in which better machining performances are accomplished with tap water due to the higher conductivity, limiting tool wear by applying low voltage values. Machining of a Titanium alloy with the use of tap water for environmental purposes is discussed in [12], regarding the optimization of working parameters. In [13], biodiesel is pointed out as a valid alternative dielectric fluid in die-sinking EDM for Aluminium alloy machining, with lower smoke and odours emanation and higher productivity, although the environmental hazard is not discussed.

Different performance behaviours have been identified in micro-EDM in contrast to EDM using water-based fluids. In particular, when water is used in micro-EDM, corrosion and metal dissolution occur onto the workpiece surface, due to electrolysis activated by water, which is chemically considered as a weak electrolyte. Moreover, in order to privilege the erosion more on the workpiece rather than on the tool in micro-EDM, the workpiece is usually positively polarized while the tool is set to negative. However, when using water, the constant electrodes polarization, the temperature and the discharge conditions favour electrochemical reactions which induce metal corrosion and thus leading to a lack of dimensional and surface accuracy of the features. It was observed by several authors that this problem can be solved by operating the alternation of polarization between tool and workpiece during micro-EDM machining. Nonetheless, this action has its heavy drawback in the dramatic increase of the tool wear, being also set to positive. Taking into account all these issues, a solution has been presented in [14], where the development of a new high frequency bipolar pulse generator able to cope with the triggering of severe metal corrosion is discussed. A similar approach was proposed in [15]; the method developed by the authors concerns the implementation of a novel short voltage pulse generator used in micro-EDM machining of holes on tempered carbon steel workpiece using a W cylindrical rod tool. The electrochemical reaction triggered by the erosion process in water is modelled as series of the parallel plate capacitors and a resistance. The capacitances represent the electrode-solution interfaces at both sides (workpiece and tool). So, this additional part of the circuit can be charged or not, depending on their charging time τ (which is dependent on capacitance and resistance values). The obtained results underline that if the pulse width is significantly smaller than τ, the effects of corrosion on the electrodes and consequent dissolution of metals due to the electrolysis of water can be effectively suppressed. In this case, no polarization inversion is required, although a specific generator pulse circuit has to be conceived.

In the present work, micro-EDM machining of micro-slots on a hardened steel thin plate has been performed using four fluids, such as tap water, tap water with Garnet, deionized water and deionized water with Garnet and hydrocarbon oil. Garnet is an almandine granite commonly used as abrasive in the micro-AWJ machining and, in current literature, it has not yet been considered in micro-EDM to our knowledge. The experiments have been performed using two different machining regimes to evaluate the performance in terms of material removal rate (MRR) and tool wear ratio (TWR). Also, the crater size and dimensions have been estimated using confocal microscope. All trials have been replicated six times per each fluid and each energy level and performed without tool wear compensation. Also, the surface quality of the machined features and the tool have been inspected to identify the presence of metal dissolution, effects of oxidation and eventual layer recast.

Nomenclature

σ	Conductivity
V_{drill}	Workpiece volume removed by drill
V_{trench}	Workpiece volume removed by trench
A_{sector}	Area of the red circular sector in Fig. 4
d	Distance between the two circumferences (Fig. 4)
s	Thickness of the steel plate
MRR_{drill}	Material removal rate calculated for drilling
MRR_{trench}	Material removal rate calculated for trench
t_{drill}	Recorded drilling time
t_{trench}	Recorded trench time
TWV	Calculated tool wear volume loss
TWR	Tool wear ratio
$\langle D \rangle$	Average measured diameter of craters
σ_D	Standard deviation of measured craters diameters

2. Machining set-up

The micro-EDM machine used for the experiments is the Sarix SX 200 HP. The machine has been equipped with a specifically designed hydraulic circuit, conceived to enable fast source liquid exchange, so that the water-based fluid used for machining can flush in a closed loop, separated from the circuit pump devoted to hydrocarbon oil (Fig. 1). A stainless steel holding plate, mounted on the original one, in order to guarantee parallelism, is enclosed in a bowl in order to keep the water-based machining zone separated. Flow rate regulation is automated, enabling also sinking EDM machining. Regarding the machining process, micro-slots are realized on a hardened steel (AISI 301) plate having thickness of 0.25 mm. The tool is a cylindrical rod made of WC with a diameter of 0.4 mm. Tap water, tap water with Garnet, deionized water and deionized water with Garnet have been exploited for flushing. The particles size, i.e. the mesh, chosen for the present experiments varies from 0.2-0.6 mm. The conductivity and temperature values of all water-based fluids, with and without Garnet, have been measured using a specific conductivity probe (Tetracon 325) and reported in Table 1. In the cases where tap and deionized water have been mixed with the quantity of Garnet typically used in micro-AWJ (130 g per litre of water), the mixtures have been carefully prepared: in particular, we poured small quantity of Garnet of the total required in order to monitor the solution homogeneity as the concentration was increased. We observed that independently of the Garnet concentration, all sandy particles precipitated in the tank bottom. Once the final concentration has been achieved, the solution has been shaken for five minutes. Then the conductivity and temperature have been measured every 5 min, up to 20 min (Fig. 2). It has been noticed that, even after shaking, Garnet particles deposited on the tank bottom after 20 min, while a dusty part remained suspended in the water. Moreover, the presence of the abrasive does not alter the conductivity of the tap water considerably, while in case of deionized water this value changes of $\Delta\sigma$=30µS/cm.

At the end of each set of trials involving a specific water-based fluid, the water-based fluid conductivities have been measured once again. On the contrary, deionized water conductivity measured at the end of the experiments changes of $\Delta\sigma$=10µS/cm and this variation is due to the presence of metal particles removed by the workpiece.

Two different machining regimes, indicated by the energy level indexes E365 (roughing) and E206 (semi-finishing) have been selected. The corresponding main process parameters, voltage, current, pulse width, frequency and gap, are reported in Table 2. These values have been set considering micro-EDM trials and performances previously done on hardened steel and obtained using hydrocarbon oil. It is worth stressing that for the semi-finishing regime, the pulse width has been reduced to the lowest value allowed by the micro-EDM machine in order to avoid the triggering of the electrolysis, as suggested by [15]. For the same reason, also the frequency value has been increased. This choice leads to the reduction of the duty cycle and consequently to a decrease of the pulse number during the erosion process.

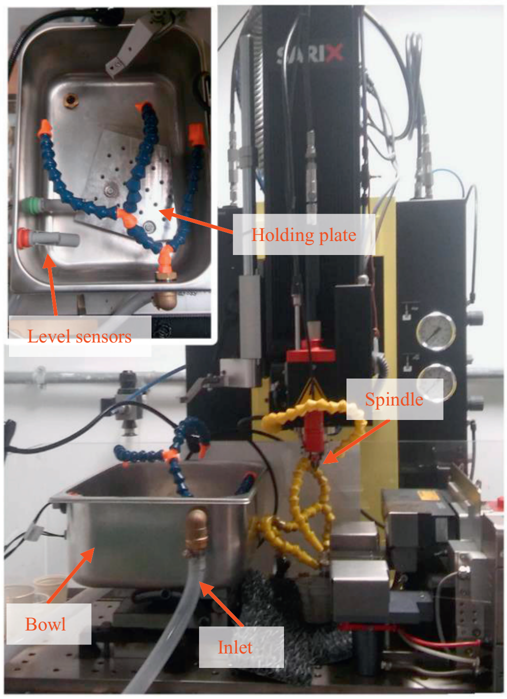

Fig. 1 Sarix SX 200 HP micro-EDM machine equipped with the customized hydraulic water pump system and devoted tank.

Table 1. Conductivity measures of the used fluids after machining.

Before/after machining	Tap Water	Tap Water with Garnet	Deionized W.	Deionized W. with Garnet
Before	388µS/cm	390 µS/cm	18,0µS/cm	48,4µS/cm
After	402µS/cm	400 µS/cm	28µS/cm	96µS/cm

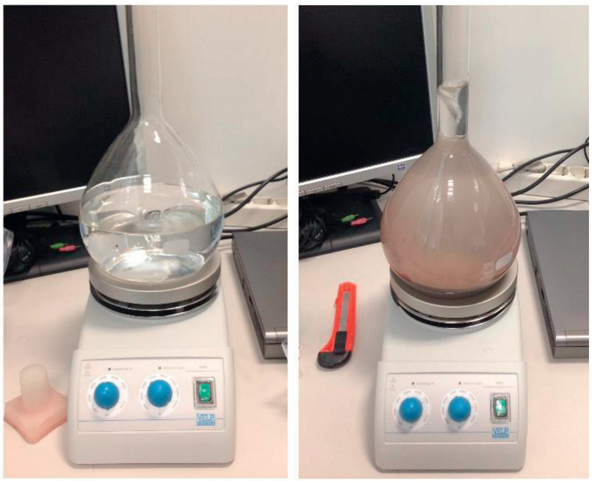

Fig. 2 Shaking of the water-based liquid without (a) and with Garnet (b).

Table 2. Machining process parameters.

Process	Voltage [V]	Current [index]	Width [µs]	Frequenc y [kHz]	Gap [index]
E365	150	80	6.6	90	60
E206	130	50	0,5	150	65

Fig. 3 reports the snap shots of the trials replicated three times per each energy level and fluid. The initial part of each feature has been realized via micro-EDM drilling (upper edges in all figures), while the rest of it has been machined via through-trench. All processes have been performed without any tool wear compensation strategy, underlined by the tapering of the slots due to the reduced working section of the tool occurring during through-trench. The difference among the slot lengths is due to tool wear phenomenon as well as occasional instability of some processes, observed in particular when deionized and tap water were used.

The machining performance have been evaluated in terms of material removal rate (MRR) and tool wear ratio (TWR). MRR has been estimated considering the material removed by the workpiece during drilling and through trench, separately (Fig. 4), and then dividing them for the respective machining times (t_{drill} and t_{trench}). The procedure is summarized by the following equation (1)-(4):

$$V_{drill} = \pi R^2 s \tag{1}$$

$$V_{trench} = \left((R + r) \cdot d + \frac{1}{2}\pi r^2 - \frac{1}{2}\pi R^2 \right) \cdot s \tag{2}$$

$$MRR_{drill} = V_{drill} / t_{drill} \tag{3}$$

$$MRR_{trench} = V_{trench} / t_{trench} \tag{4}$$

The worn volume from the tool have been calculated taking into account the tool length shortening and the tip section reduction, in the following fashion:

$$TWV = \left(\pi R^2 - \pi r^2\right) \cdot s \tag{5}$$

$$TWR = \frac{TWV}{V_{drill} + V_{trench}} \tag{6}$$

The total volume removed from the workpiece is the sum of the equation (1) and (2).

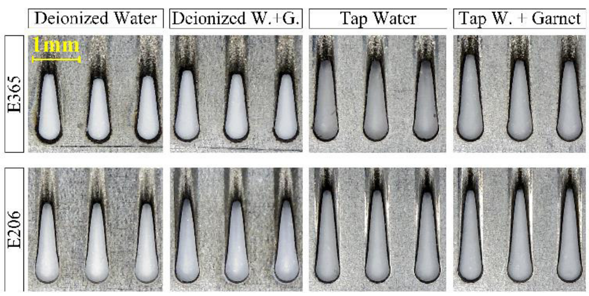

Fig. 3 Snap shots of the trials per each energy level and fluid.

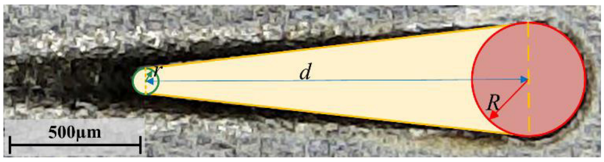

Fig. 4 Cavity details for the calculation of MRR and TWR. The workpiece volume removed by drilling is highlighted in red, while yellow filling indicates the volume removed by trench.

3. Results and Discussion

Figures 5 and 6 show the diagrams related to MRR for both approaches, drilling and through trench respectively, and for the two set of parameters (shortly identified by the energy level index E365 and E206), plotted versus the electrical conductivity of the water-based fluids. In the case of micro-EDM drilling using roughing regime (E365 – Fig. 5a) similar values of MRR have been found, although a slight increase can be observed in case of tap water with Garnet. Nonetheless, the standard deviation in these experiments is quite high, indicating an issue about repeatability of trials. The analysis on through trench (Fig. 5b) shows similar trend indicated in drilling; however, the liquids added with Garnet exhibit a slightly lower MRR in comparison to their bare counterparts. When semi-finishing regime is considered (Fig. 6), a clear behaviour of MRR versus electrical conductivity is highlighted for both drilling and through-trench approaches. In fact, MRR decreases as the electrical conductivity value increases. In these cases, the MRRs of the added deionized water exhibit a decrease with respect to the pure one. On the contrary, no relevant variation can be noticed for tap water and tap water with Garnet, which show very similar MRR. Generally, as it can be noticed, MRR increases according to the water conductivity decrease, especially when the micro-EDM machining is performed considering lower energies.

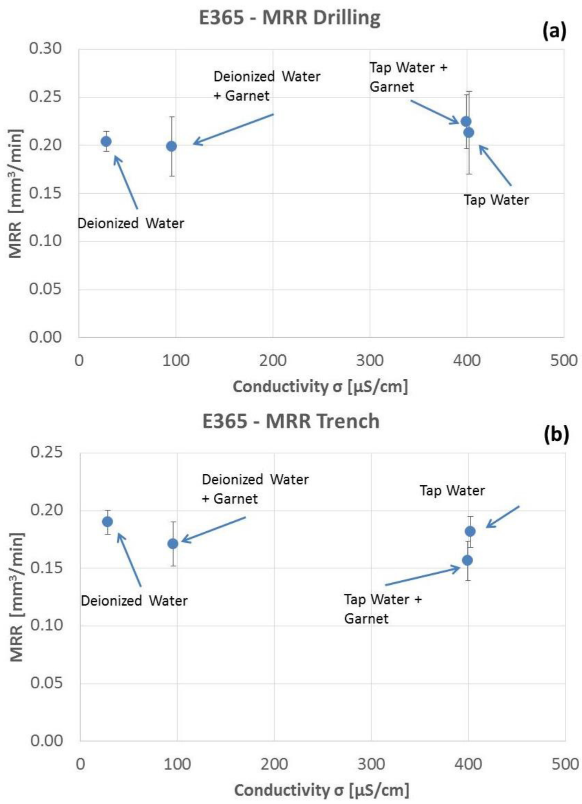

Fig. 5 MRR calculated for set of parameters indicated by E365 drilling (a) and through-trench (b) with different electrical conductivities (i.e. flushing fluids).

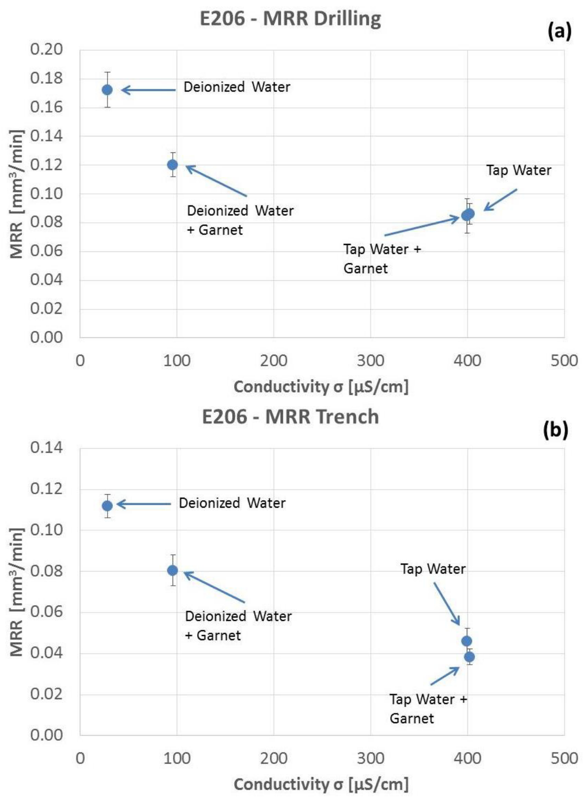

Fig. 6 MRR calculated for set of parameters indicated by E206 drilling (a) and through-trench (b) with different electrical conductivities (i.e. flushing fluids).

This behaviour in MRR using water-based fluids is due to the plasma channel formation and dimension, which is very different compared to hydrocarbon oil. Indeed, when hydrocarbon is used, the energy density of the discharge is confined and enhanced by the presence of the dielectric; in this case, typically the number of sparks is small in the beginning but it tends to increase as the metal debris diffuses in the channel. A whole different behaviour is expected by the plasma channel in water fluids, as also stressed in [16]. First, the plasma channel has not the same dimension, since it is more expanded than that observed in the hydrocarbon dielectric. The electric field distribution is non uniform in the conductive fluid, due to the presence of the ions, which increase their concentration as the metal debris are removed from the workpiece. This effect induces a differential potential for the discharge lower than the value set by the open voltage V applied in the gap. The conductivity of the water fluid implies the presence of a high resistance between the electrodes. In case of hydrocarbon oil, the workpiece-tool interface can be typically described by a capacitive circuit with a huge resistance (due to the debris diffusion). When water is considered, although the resistance value is high, it is still sufficient to decrease the breakdown voltage, thus affecting the effective energy density delivered by the discharge during the erosion process. This has consequences on the discharge time, which is actually decreased compared to the set value (pulse width) and on craters shape and dimensions, which are expected to be different. When the gap between tool and workpiece is kept constant, the probability of a discharge to occur in water-based fluid is ideally enhanced by higher electrical conductivity as the number density of ions is greater and thus it promotes the ignition. However, even although the sparks are initially favoured by these conditions, after some time, the contamination of the debris, the electrolysis effects and eventual oxidation of the surface affect the discharge occurrence [17]. All the described physic is more evident in case of semi-finishing regime, since the energy density is less and the machining evolution is slower.

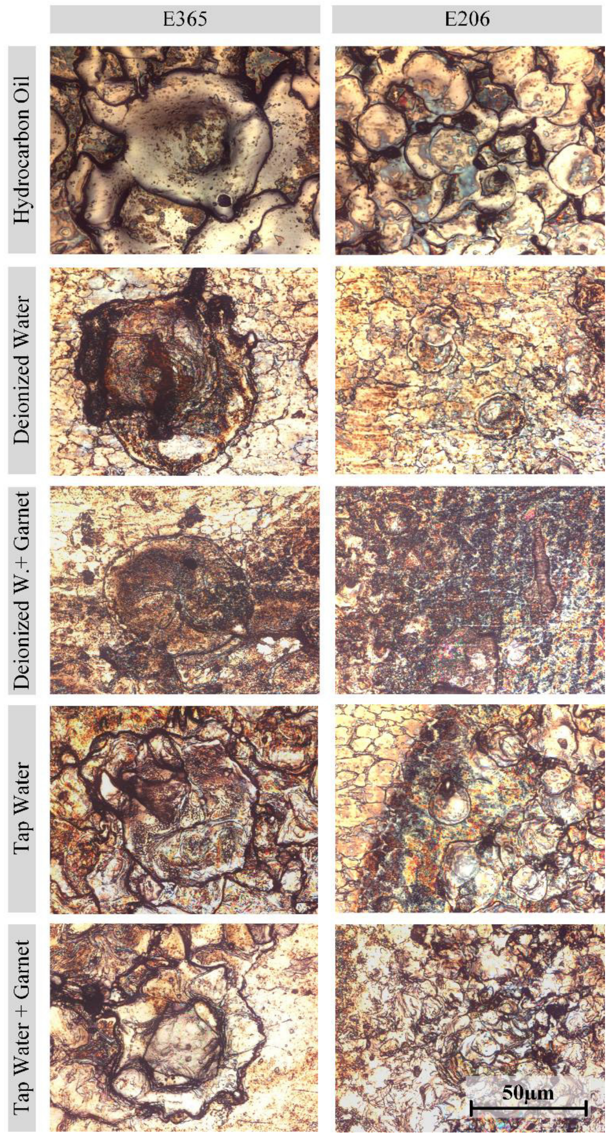

Fig. 7 Confocal microscope pictures of craters considering E365, E206 and different flushing fluids.

Table 3. Crater diameters for the different machining processes

	Initial σ [µS/cm]	E365 <D> [µm]	E365 σ_D [µm]	E206 <D> [µm]	E206 σ_D [µm]
Hydrocarbon Oil	-	66	5.7	22	1.9
Deionized Water	18	69	5.6	20	1.7
Deionized W.+ G.	48	59	3.6	16	1.1
Tap Water	388	59	5.4	18	1.8
Tap W. + Garnet	390	61	9.5	16	0.6

Fig. 7 reports the view of craters including those obtained using hydrocarbon oil and same process parameters for comparison. Craters for water-based fluids are not characterized by melt pool effect observed in the hydrocarbon case; moreover they are less circular and deep. Table 3 shows the estimated diameters of the craters performed using the confocal microscope ZEISS CSM 700. The surfaces machined using semi-finishing regime and water-based fluids added with Garnet display dark areas, which are reasonably due to deposited layers (mainly caused by the presence of carbon released by the tool during machining) and overlapped small craters, which make the measurement quite troublesome. The smallest crater dimension are visible for both water fluids added with Garnet. The larger crater values are measured for oil and deionized water, in case of semi-finishing and roughing.

Fig. 8 reports the TWR versus electrical conductivity values of the fluids related to all experiments. Fig. 8a shows that TWR values are generally very small when water-based fluids are used. For all considered machining regimes, TWR slightly increases when deionized water with Garnet is used. However, the increase is not significantly relevant, in particular in case of roughing, which also shows high dispersion of values. Small TWR is reasonable, since the tool is consumed during the erosion process, but it is not affected by other chemical phenomena, such as electrolysis and corrosion occurring onto the workpiece. Moreover, in all trials, it has been noticed the presence of an oxidation layer deposited onto the tool tip (Fig. 9), which protects it from wearing, although it affects the discharge rate.

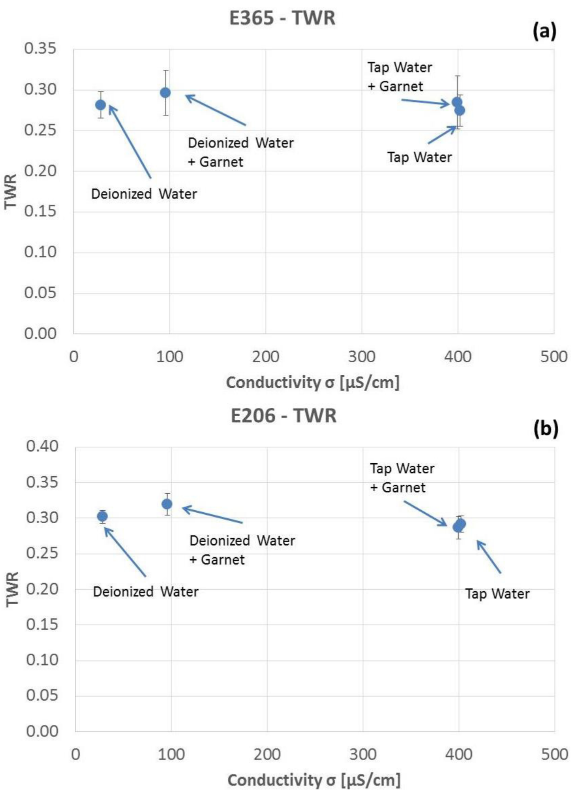

Fig. 8 TWR for E365 (a) and E206 (b) versus electrical conductivity (different flushing fluids).

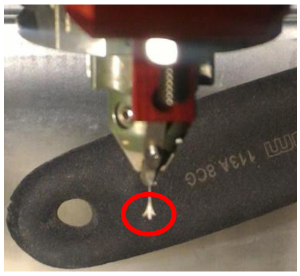

Fig. 9 Oxidation layer deposited on the tool tip.

4. Conclusions

In this work, a preliminary study about the impact of water-based fluids added with abrasive in micro-EDM manufacturing has been presented. The aim is the exploration towards a hybridization of micro-EDM and micro-AWJ technologies. Hence, a hardened steel thin plate has been machined via micro-EDM drilling and through-trench considering different flushing fluids: deionized water, tap water, deionized water with Garnet, tap water with Garnet. The Garnet concentration per litre of water considered in the micro-EDM experiments is the same as required in micro-AWJ machining. The electrical conductivities of the water-based fluids have been measured before and after machining, and these values have been then linked to the machining performance. The micro-EDM trials have been carried out considering two machining regimes, roughing and semi finishing. The evaluation of MRR underlined an inverse relation between electrical conductivity values and material removal rate, in particular when semi-finishing is used. On the contrary, TWR was found to improve when the electrical conductivity of the water-based fluid is lower.

The inspection of surface quality and crater size and shape show that when deionized and tap water fluids with Garnet are used, the machined area is affected by a deposited layers, while elliptical and less deep craters are present in case of deionized and tap waters compared to hydrocarbon ones. Nonetheless, in these cases, crater dimensions seems to be more dependent on machining regime rather than on the type of flushing fluid. Nonetheless, the present results show the feasibility of a combined use of micro-AWJ and micro-EDM, although an optimization of process parameters and settings is still required to improve machining performance when a high degree of feature accuracy is required.

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