Investigation on the migration of material from tool to workpiece in micro-EDM drilling

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Electrical Discharge Machining (EDM) is a process used to remove material by means of t electrical discharges between the tool electrode and the workpiece. During the process, particles of the electrode migrates to the workpiece and vice versa, causing contamination. This can result in modifications of the physical and mechanical properties of the workpiece surface. Aim of this work is to study the migration of material from the tool to the workpiece during the execution of micro holes using micro-EDM. Micro holes were executed on stainless steel and titanium sheets; tubular electrodes made of brass and tungsten carbide were used while peak current and voltage were varied. The surfaces were analysed quantitatively using energy-dispersive x-ray (EDX) for detecting the surface composition. The migration of material was observed. Peak current and voltage resulted to affect in non–homogeneous way the morphology and the distribution of the elements on the hole surface.

KEYWORDS: MICRO-EDM – MICRO-DRILLING – PARTICLES MIGRATION – SURFACE MODIFICATION – PROCESS PARAMETERS – COPPER ELECTRODE – TUNGSTEN CARBIDE ELECTRODE.

INTRODUZIONE

The panorama of the new production technologies is rapidly growing. Recent reviews [1,2] pointed out how advanced manufacturing techniques are mainly aimed to manufacture of innovative products and application of creative principles. The market interests in terms of design flexibility through additive manufacturing techniques, advanced joining techniques, microfeaturing, materials surface modification, and miniaturisation of components are driving such evolution, leading to the necessity of more comprehensive approaches to the relation between production processes and material behaviour. The modification of surface properties of materials due to the use of innovative production techniques leads to several consequences on the mechanical, electrochemical and physical behaviours of the materials. Significant effects have been noticed by several authors on both the fatigue behaviour and corrosion behaviour of light alloys due innovative manufacturing processes [3–8]. These phenomena can be consistently enhanced in the field of micro-manufacturing of components through the use of electrical discharging techniques [9] that permit the realisation of micro features with unique properties. The need for products containing micro-features has shown a noticeable and continuous growth in many fields of application, and within the different types of micro-feature, the need for products containing microholes has shown remarkable growth in some industrial sectors [10,11]. At the same time, materials with distinctive mechanical and physical properties, such as titanium- or nickel-based alloys, tungsten carbide and its composites, tool steels and other super alloys, have been developed to meet the needs of specific applications. In general, these materials have high performing properties in terms of hardness, toughness, low heat sensitivity, high fatigue and corrosion resistance with respect to other more common materials, despite they are often more difficult to be machined [12,13]. A large number of researches have been carried out to study the machinability of such materials using both conventional and non-conventional processes. Among non-conventional technologies, the Electrical Discharge Machining (EDM) is used in several industrial applications for the production of micro components, micro holes and in general features having complex shapes and high aspect ratio. The material is removed by a succession of electrical discharges

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which occur between the electrode and the workpiece, submersed in a dielectric fluid such as kerosene or deionized water. The sparks cause the melting and the vaporization of the material that is rapidly re-solidified and removed from the machining area by the dielectric flushing. Since EDM is a contact-less process, it is suitable for the machining of hard and high-strength materials, otherwise considered "difficult to cut" with conventional technologies, and micro-parts without distortion[14].

Literature reports several papers that investigate the influence of the process parameters on the machining performance. For example, in [15] the influence of process parameters and electrode size were studied. In particular, aspects such as Material Removal Rate (MRR) and Tool Wear Ratio (TWR) during the micro-EDM drilling process on stainless steel plates were investigated. An improvement in this topic was reached in [16] where an investigation on power discharge in micro-EDM stainless steel drilling using different electrodes was carried out. This index fits, with a good correlation level, all the process performance and geometric indicators. The results of this experimental research showed that electrical resistivity, thermal conductivity, and melting point of both electrode and workpiece materials have a significant effect on the process and geometric performance.

One of the problems associated with EDM is the migration of material particles from tool to workpiece and vice versa, affecting surface contamination. In recent years, many studies about this phenomenon have been carried out because, when performing EDM in the micro scale, the effects produced from the material migration can play an important role in terms of properties and quality of the workpiece machined surface.

One of the first studies about material migration was performed in [17] in 1996. In this paper an investigation about changes in chemical composition of both workpiece and tool surfaces after machining with rotating copper-tungsten electrode was presented. The contamination was due to material migration from electrode to workpiece surface and from the machined surface to the electrode. Microanalysis investigation carried out on the workpiece by means of a Scanning Electron Microscope (SEM) showed a white layer of re-solidified material adjacent to the steel matrix and the presence of tungsten and copper migrated from the electrode. In particular, the presence of tungsten was higher than copper. The same analysis was done on the electrode surface. This one showed the presence of iron and chromium coming from the workpiece.

The surface modification by a titanium coating layer onto a tungsten carbide surface by means of electrical discharge coating was analysed in [18]. Tungsten debris were produced by EDM using a dielectric oil mixed with Ti powder. Current and duty cycles were varied during this experiment. The results showed that the combination of titanium powder and carbon leads to surface roughness reduction and hardness increase.

In [19] the authors stated that the EDM process was carried out to intentionally execute a surface alloying. AISI H13 was used as workpiece material while the electrodes were made of WC/Co. A Taguchi approach was applied to analyse the data; this method enabled the identification of the influence of process parameters on the results in terms of white layer formation and material deposition and it was useful in the association of significant process factors and the levels on specific output measures. The analysis of the workpieces showed that the use of partially sintered electrodes made of WC/Co resulted in the formation of a uniform alloyed surface layer with relatively few micro-cracks and a uniform thickness. The results showed an increase in workpiece surface microhardness of about twice with respect to the base material.

The adhesion of machined material on the electrode surface was investigated in [20]. It was asserted that the debris location were not casual, but depending on its remelting in the dielectric by the secondary discharge process. This study showed a large concentration of workpiece particles in non-working areas. This indicates that the reason of deposition could not be the instant re-sticky of machined material after primary sparking.

In [21] the authors investigated how machining process characteristics and surface modification affect low-carbon steel during EDM process using semi-sintered electrodes. In addition to the classic machining characteristics (like MRR, Surface Deposited Rate - SDR, Electrode Wear Rate - EWR), it was analysed how semi-sintered electrodes influenced the surface changes in terms of micro hardness and corrosion resistance. The experiment was conducted using a semi-sintered electrode in Cu-W powders and kerosene was used as dielectric. During the process, metal particles stripped from the semi-sintered electrode solidified on the workpiece surface, to create, with the contribution of the kerosene dielectric, a layer of hardened steel. Low level of peak current and voltage ensured the deposition of the layer. On the contrary, high levels caused the proper melting of both the workpiece and the tool materials; moreover, the layer thickness resulted to be dependent on the process parameters.

In [22] the migration of tungsten from the electrode to the workpiece surface was investigated and the response of three different die steel materials to the surface modification by EDM process with tungsten powder mixed in the dielectric fluid. A spectrometric analysis of the workpiece surface showed a remarkable layer of tungsten and carbon. This study affirmed that the amount of tungsten layer was almost the same for all the considered materials and the original chemical composition of the die steel had no effects on this phenomenon. The presence of carbon and tungsten carbide layer indicated that the reaction in the plasma channel and it moves onto the workpiece surface during the pulse off-time. Finally, it was affirmed that the peak current was the most influencing process parameter for this phenomenon.

A study about the µEDM-milling process was provided in [23] through the EDX analysis. The experiment
was conducted with a cylindrical tungsten electrode and a hard die steel workpiece. The most significant process parameters considered during the experiment were energy, rotational speed, feed rate and aspect ratio. It was demonstrated that, after the machining, a certain amount of tungsten characte-

rized the workpiece surface, originally composed only of iron and carbon. The top surface showed an increase in carbon from 21.25% to 31.69% while the bottom surface showed an increase in percentage of tungsten from 4.45% to 12.78%. The cause of larger edge taper on one side was because of greater deposition of molten material on this channel side. The molten material was made to flow certain distance before solidification due to centrifugal force, so the layer's thickness wasn't the same, it is thick on one side and thin on the other side. This non-uniform re-deposition occurred for all machining conditions. The re-deposition phenomenon didn't occur on electrode surface thanks to the centrifugal force.
In [24] the authors affirmed that the composition of steel changed from the surface to the core of the workpiece. The machining tests were conducted by using copper and graphite tool electrodes and as dielectric fluid kerosene and deionized water, under the same machining conditions. This study showed the presence of carbon on workpiece surface regardless of the electrode material when machining with kerosene. But, austenite was found on surface when machining with graphite electrode and deionized water: in this case the percentage of austenite increases, whereas it decreases when machining with kerosene. In conclusion, this study affirmed that the surface was enriched incarbon from electrode when machining with hydrocarbon dielectric fluid. Carbon was effective on the formation of austenite phase within the white layer when machining with deionized water like dielectric fluid.
Several literature data covering the migration of material from the tool to the workpiece surface during micro EDM drilling are present but lack of data was noticed regarding the correlation between the microstructure and distribution of material from the tool electrode to the workpiece along the hole length as a function of process parameters.
Aim of this work is to study the migration of material from the tool to the workpiece surface during the execution of micro holes by using micro-EDM technology. Morphological and compositional analyses were performed on hole surfaces in order to assess the microstructure and the correlation between microstructure and element composition distributions along the hole length and as a function the technological parameters for EDM drilling. Different conditions in terms of process parameters, workpiece and electrode materials were taken into account: stainless steel and titanium for the workpiece, brass and tungsten carbide for the electrode.

Experimental research

The micro EDM machine used in the experimental campaign was a Sarix SX-200. Patterns of micro holes were executed on both stainless steel (AISI 304) and titanium (ASTM B265 Grade 2) sheets having a thickness equal to 1 mm. Table 1 shows the physical and mechanical properties of the two workpiece materials. Two electrode materials, brass and tungsten carbide, having different thermal, physical and electric characteristics, were used (Table 2). The electrodes were tubular, with an outer diameter equal to 0.3 mm and an inner diameter equal to 0.12 mm.

Tab. 1 – AISI 304 and titanium ASTM B265 Grade 2, physical and mechanical properties

Physical Property	AISI 304	Titanium ASTM B265 Grade 2
Density	8 g/cm^3	4.5 g/cm^3
Melting range	1455 °C	1668 °C
Specific heat	0.5 J/g-°C	0.54 J/g-°C
Tensile strength	505 MPa	344 MPa
Young modulus	193 GPa	108 GPa
Hardness Vickers	129 HV	145 HV
Electrical resist.	72·μΩcm	60 μΩcm

Tab. 2 – Physical properties of the electrode materials

Physical Property	Brass C26800	Tungsten Carbide WC94Co6
Density [g/cm^3]	8.47	14.8
Melting point [°C]	905	2867
Electrical resistivity [Ωcm]	6.63*10-6	20*10-6
Thermal conductivity [W/mK]	121	70
Specific heat [J/(g°C)]	0.38	0.3

A full combination of electrode and workpiece materials was considered in the experimental plan (Table 3). During the experimental campaign, peak current (I [index]) and voltage (V [V]) were varied on two levels (I = 80 – 100, V = 80 – 100 V). The process parameters kept fixed are reported in Table 4. Finally, hydrocarbon oil was used as dielectric with an internal washing pressure equal to 6 bar.

Tab. 3 – Combination of workpiece and electrode materials

	Workpiece Material	
Electrode Material	Stainless (AISI 304)	Steel Titanium (ASTM B265 Grade 2)
Brass	Peak Current - Voltage High-High / Low-Low / High-Low / Low-High	
Tungsten Carbide		

Tab. 4 – Fixed process parameters

Parameter	Value
Energy	365
Polarity	- (neg.)
Width [μs]	5
Frequency [kHz]	120
Gain	100
Gap [%]	60
Spindle rotational speed	100%
Regulation	03-01

A program for the automatic execution of the holes using the different technologies was implemented into the Sarix EDM machine and, at the end of each drilling operation, the electrode tip was cut using the wire EDM unit to restore the same initial conditions for all the tests.
After machining, the workpieces were cleaned with acetone using ultrasonic cleaner. Finally, the machined surfaces were analysed quantitatively using energy-dispersive x-ray (EDX) for detecting of surface composition. The analysis was conducted on both machined and not machined surfaces to investigate the modification in the element composition of the surface.
A set of surface roughness measurements was also carried out on the hole surfaces along the axial direction by means of a roughness meter (Form Talysurf S21 PGI 420) with interferometric sensor.

Results and discussions

Titanium

Fig. 1 shows the SEM images of the craters on the side walls of the micro holes executed on titanium plates using tungsten carbide electrode and different process parameters in terms of peak current and voltage. The level of peak current has effect on the surface morphology. Using low level of peak current, the surface is more indented while, using the higher value, larger craters appear and the morphology seems to be smoother. The surfaces show some fractures for both the conditions. In order to evaluate the migration of material from the tool to the internal surface of the micro holes and its homogeneity distribution, different spectra were taken for each hole.
Fig. 2 reports an example of EDX spectrum analysis of two areas of a micro hole obtained using low values of peak current and voltage. Spectrum 4 refers to a localized spherical particle on the surface.

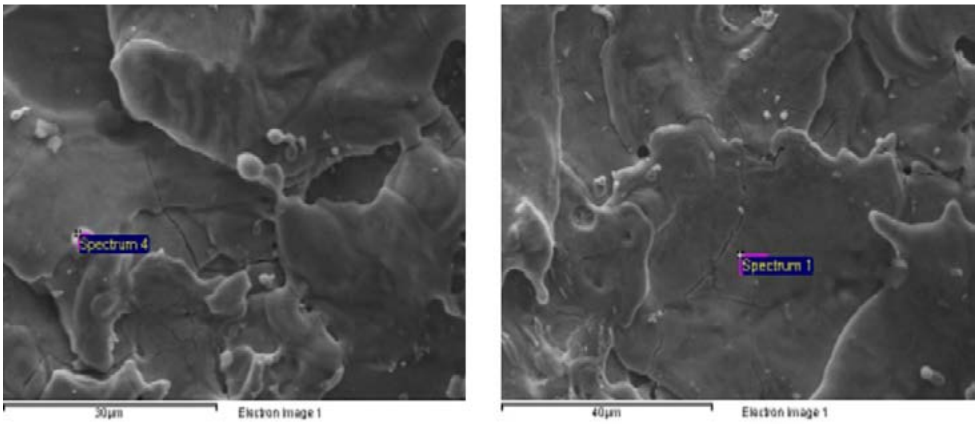

Fig. 1 – SEM images of the micro holes on titanium, tungsten carbide electrode, peak current and voltage (a) Low/Low (b) High/Low.

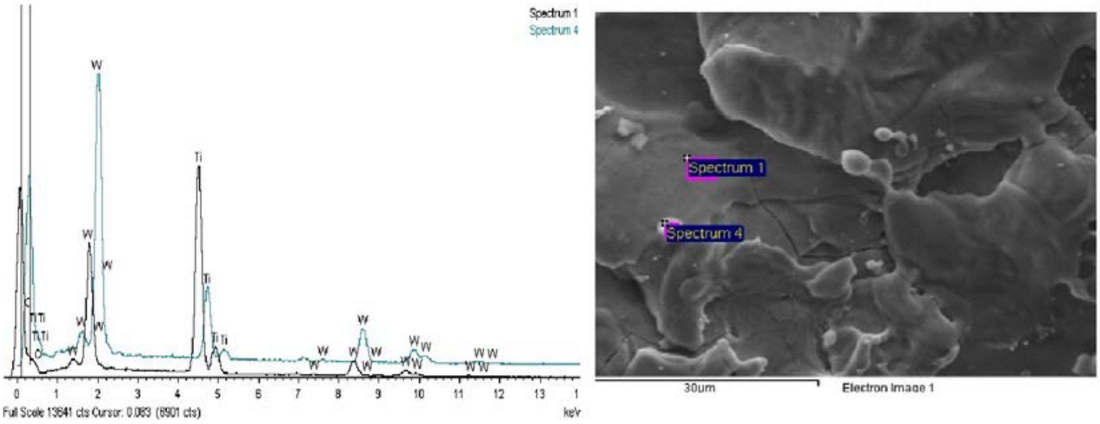

Fig. 2 – EDX spectrum of two micro hole areas on titanium (tungsten carbide electrode, peak current: low, voltage: low).

The migration of tungsten carbide particles from the electrode to the micro hole surface during the drilling operation is confirmed. It must be noticed that the amount of tungsten and the ratio between titanium and tungsten are not the same for the two spectra. Moreover, there is an influx of carbon and oxygen at the edge of the micro hole. This fact can be ascribed to traces of organic fluid such as dielectric.

As regard titanium machined using brass electrode, the SEM images for two experimental conditions are reported in Fig. 3. In this case, no significant differences have been observed by varying the process parameters.

A comparison of the EDX spectrum analysis executed on two areas of the same micro hole is reported in Fig. 4. Also in this case, elements from the tool electrode (Cu and Zn) were found on the workpiece. A not homogeneous distribution of the chemical elements in the same hole is confirmed.

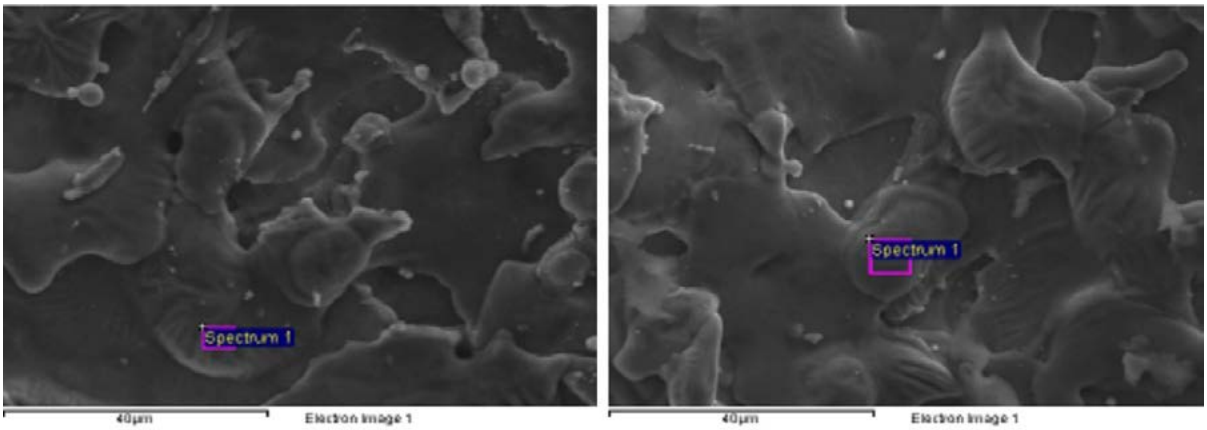

Fig. 3 – SEM images of the micro holes on titanium, brass electrode, peak current and voltage (a) Low/Low (b) High/Low.

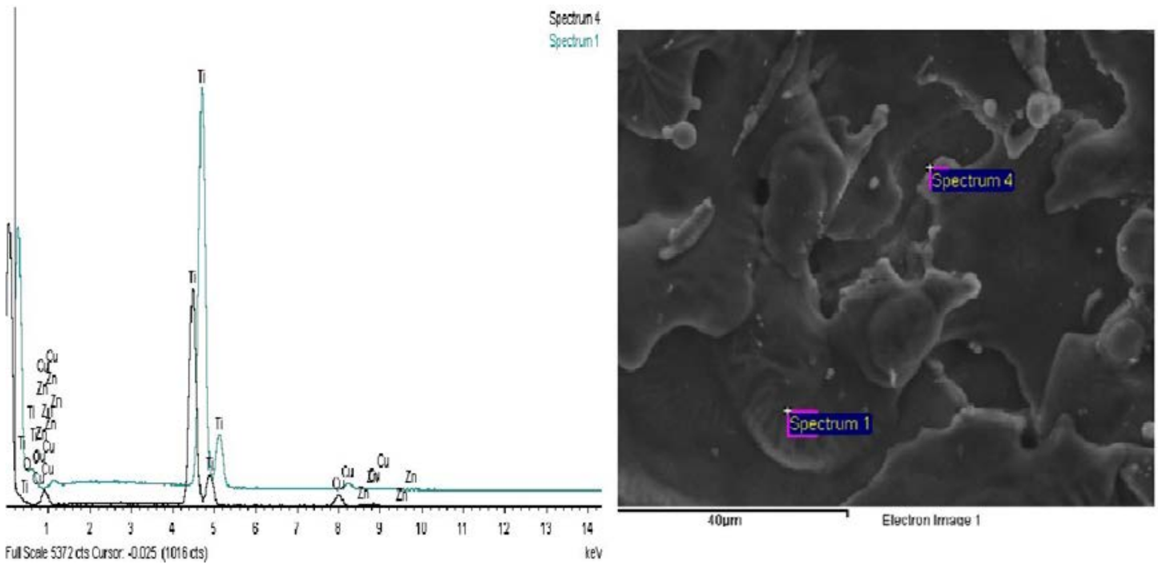

Fig. 4 – EDX spectrum of two micro hole areas on titanium (brass electrode, peak current: high, voltage: low).

Stainless Steel

The SEM images regarding holes on stainless steel, obtained using a WC electrode and different EDM process parameters, are reported in Fig. 5. The dimension of the craters increases for increasing values of the power discharge (peak current and voltage). The EDX spectrum analysis for stainless steel, using WC electrode at high level of peak current and voltage in two zones is reported in Fig. 6. Significant differences between the two spectra are found.

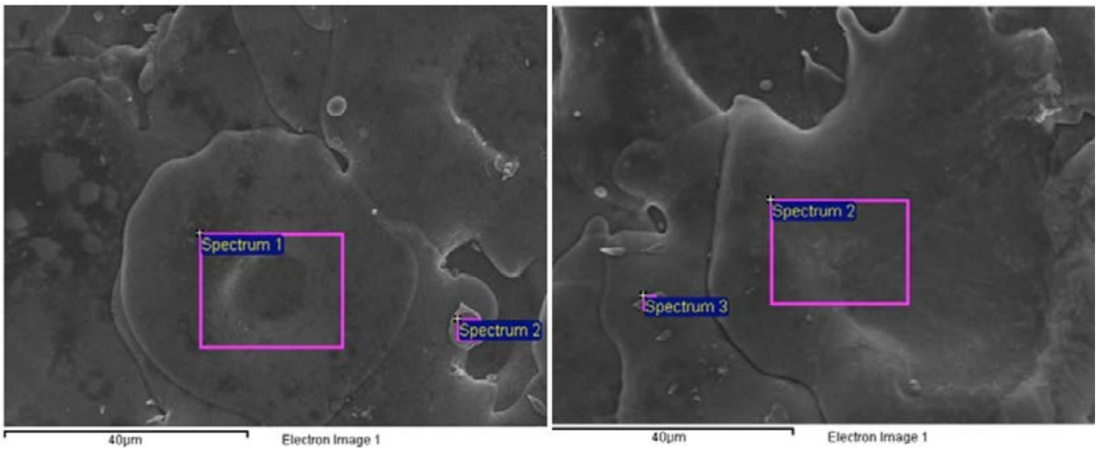

Fig. 5 – SEM images of the micro holes on stainless steel, tungsten carbide electrode, peak current and voltage (a) Low/Low (b) High/High.

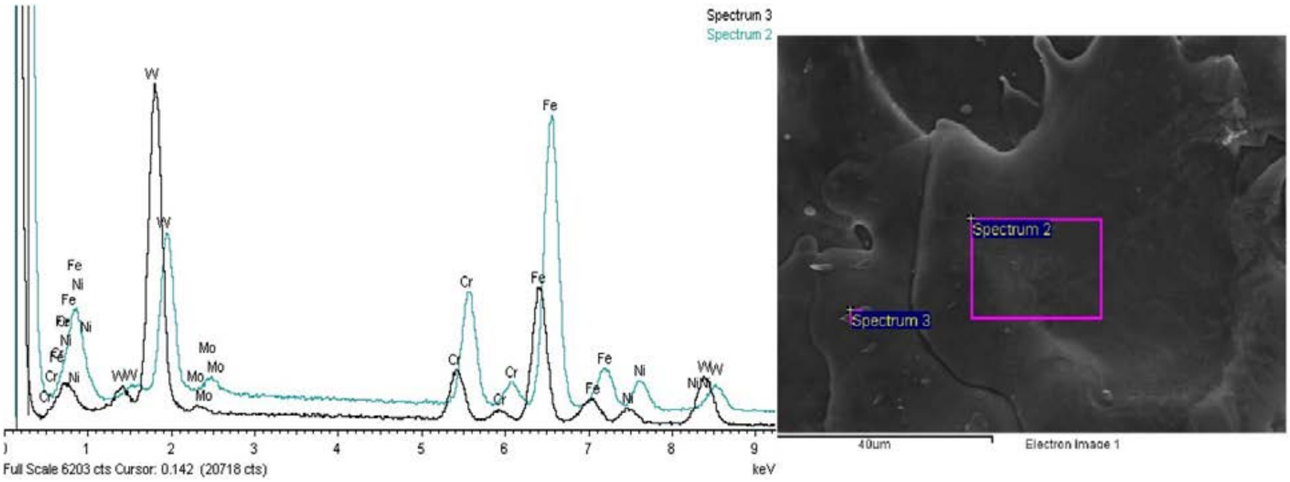

Fig. 6 – EDX spectrum of two micro hole areas on stainless steel (tungsten carbide electrode, peak current: high, voltage: high).

As an example, the distribution of tungsten on the stainless steel workpiece as a function of the distance from the hole wall (moving through the base material) is presented in Fig. 7. The vertical axis represents the ratio between the peak of tungsten detected in the proximity of the hole with respect to the baseline. It is possible to notice that the hole surface is affected for a depth of about 5 μm and the tungsten profile distribution differs depending upon the EDM process parameters.

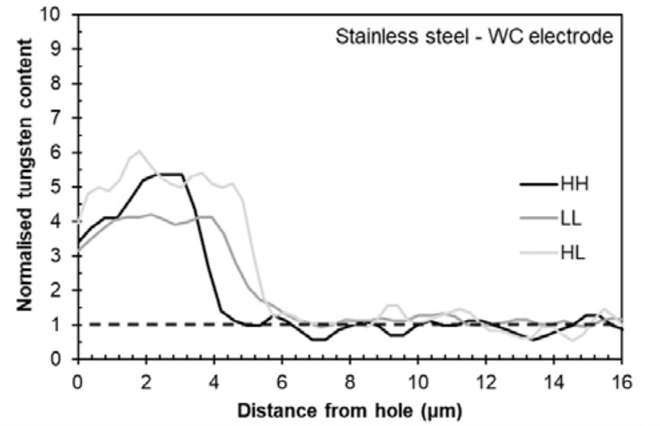

Fig. 7 – Normalised distribution of tungsten on the stainless steel workpiece as function of the distance from the hole wall, detected by EDX, varying peak current and voltage.

Finally, SEM images of stainless steel holes obtained using brass electrode and different process parameters are reported in Fig. 8. No significant differences are visible: for both cases the surfaces are smooth and there are some large isolated particles.

A comparison of the EDX spectrum analysis executed on two areas of the same micro hole is reported in Fig. 9.

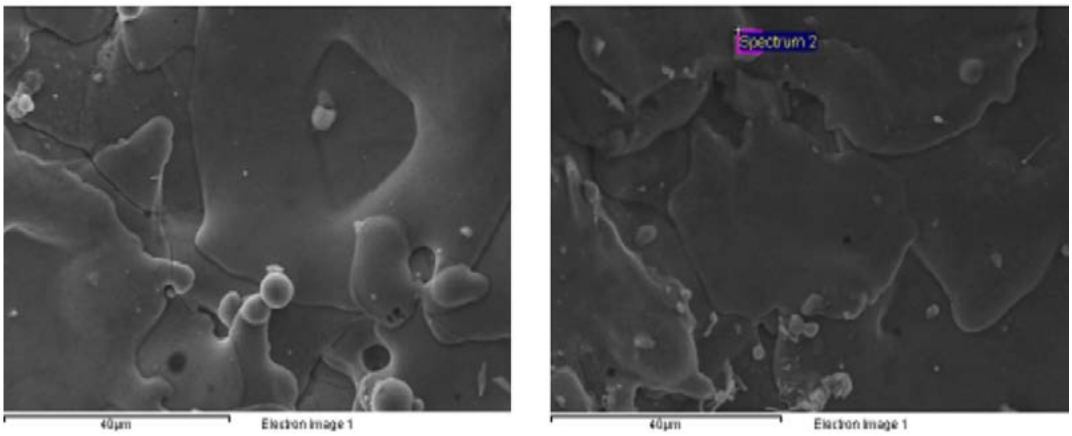

Fig. 8 – SEM images of the micro holes on stainless steel, brass electrode, peak current and voltage (a) Low/Low (b) High/High.

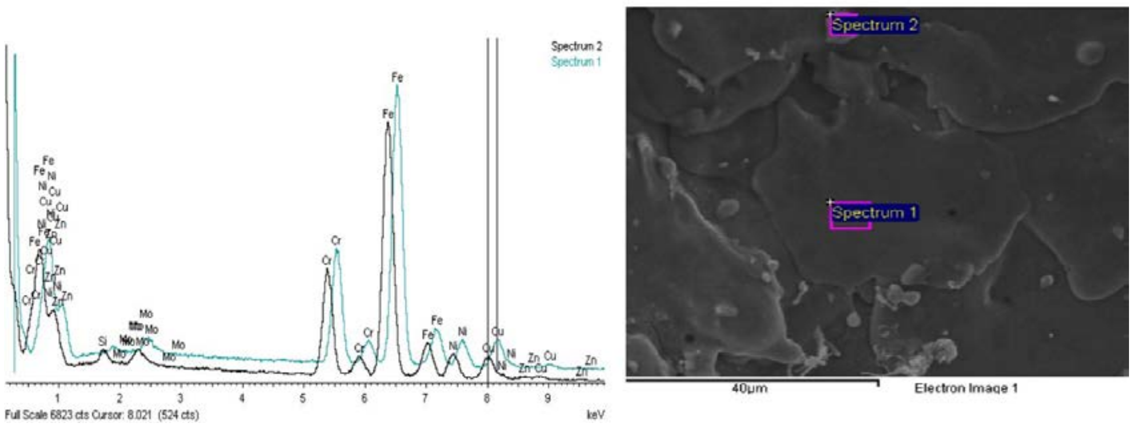

Fig. 9 – EDX spectrum of two micro hole areas on stainless steel (brass electrode, peak current: high, voltage: high).

Surface roughness analysis

A surface roughness analysis was carried out on the hole surfaces along the axial direction (Fig.10).

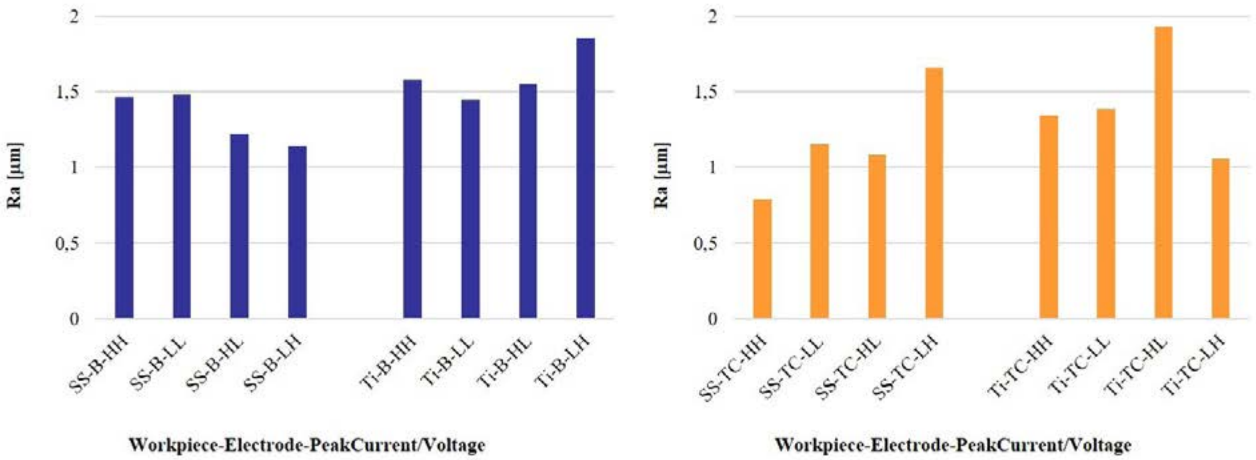

Fig. 10 – Axial surface roughness (Ra) of holes obtained on both stainless steel (SS) and Titanium (Ti) using different process parameters combination and different electrodes.

The experiments structure is a 2-level 4-parameter plan without repetition and it can be analysed using ANOVA techniques. Table 5 shows the process parameters and their first-order interactions, together with the p-values of the corresponding estimate. Although p-values are relatively high, it can be noted that the
most significant factors are the work material (WP) and its interaction with Peak Current (WP*I).

Tab. 5 – ANOVA p-values for main effects and 1st order interactions (ordered by increasing p-values).

Variable name	Effect	p-value
WP	work mat.	0.204
WP*I	interaction	0.342
EL	electrode mat.	0.405
EL*V	interaction	0.512
I*V	interaction	0.589
WP*V	interaction	0.717
V	voltage [V]	0.817
I	peak current [#]	0.883
WP*EL	interaction	0.949
EL*I	interaction	0.994

Conclusion

The migration of material from tool to workpiece surface during the execution of micro holes, using EDM technology with different process conditions, workpiece and electrode materials, was confirmed. Peak current and voltage affect the morphology and the distribution of the chemical elements on the internal surface of the hole. The elements distribution is not homogeneous and it is strictly dependent upon microstructure, which is mainly determined by the process parameters. In addition, a certain variability of tool elements distribution from the hole surface to the bulk material, as a function of the process parameters, was noticed. According to this evidence, only qualitative analysis of the distribution and amount of material transferred from the tool to the workpiece can be performed at this stage and no quantitative correlation can be defined i.e. between transferred metal and electrode consumption. The optimization of the process parameters is fundamental to attain a more homogeneous microstructure, which lead also to more even metal distribution in the hole and improves physical and mechanical properties of the workpiece surface. When roughness data are studied, work material seems to have the most relevant effect.

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