ANALYSIS OF THE SURFACE OF MICRO EDM HOLES

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In micro EDM drilling, particular attention should be made to characterize the hole not only from a macro and micro geometric point of view but also as regards the integrity of the internal surface of the hole. The analysis of the internal surface of micro EDM holes is the aim of this paper. Micro holes were executed on the interface line of two coupled titanium sheets in order to have free access to the internal surface after the drilling operation. The effects of the type of machining (roughness or finishing) and the effects of the washing pressure through the internal diameter of the electrode on the internal surface of the hole were investigated. The analysis was conducted by SEM images, observation of the craters size and the measurement of the surface roughness. Finally, EDS analyses on both the workpiece and the electrode tip confirmed the material migration in a bidirectional way from the electrodes.

KEYWORDS

micro-EDM, micro-drilling, surface modification, material deposition, process parameters, tungsten carbide electrode

1 INTRODUCTION

EDM (Electrical Discharge Machining) uses electrical discharges to remove material from the workpiece. It is possible to machine only electrically conductive materials regardless of the hardness [Choudhary 2014]. The electrical discharges take place between an electrode (tool) and the workpiece submerged into dielectric fluid. The discharges occur when the voltage between the anode and the cathode is higher than the breakdown voltage. The dielectric is essential also to remove the material that solidifies into the dielectric forming debris [Tiwary 2018]. The material is removed not only from the workpiece but also from the electrode causing wear. A particular application of technology consists of the microdrilling. Micro holes having diameter lower than tenths of mm up to some tens of µm with high aspect ratio and accuracy find application in several fields, from aerospace to automotive, from medical to in general precision mechanics.

Various technologies can be employed for micro-drilling, generally classified into thermal and non-thermal methods. Among non-thermal technologies, micro-AWJ (Abrasive Water Jet) is ideal for machining non-conductive, heat-sensitive, and brittle materials, offering versatility in material choice and no thermal damage [Fard 2025]. Micro-EDM is particularly suitable for hard and conductive materials offering tight tolerances and fine features but possible modification on the surface must be taken into account.

EDM performance is in general evaluated considering the MRR (Material Removal Rate) and the TWR (Tool wear ratio) that represents an efficiency index. It is calculated as the ratio between the volume of material removed from the electrode and that removed from the workpiece [Tsai 2004]. From a geometric point of view, the diameter of the hole with respect to the electrode diameter and the taper rate are taken into account. Moreover, considering the nature of the process, the analysis of the integrity and the chemical analysis of the surface can be essential to deeply understand the removal process.

The surface topography is a very important task considering that it influences the machining time, the cost, the product life and its reliability [Jaware 2015]. Moreover, the integrity of the workpiece material should be taken into account. The nature of the dielectric influences the hardness of the obtained surface. In the case of hydrocarbon oil, the surface shows higher microhardness than the case of water due to the formation of carbides [Al-Amin 2021, Kumar 2019].

In [Mascaraque-Ramirez 2015], the surface integrity was evaluated taking into account the surface roughness of the machined surface and the surface finish gets worse with the increase of the current intensity of the discharges. The authors noted that both the surface roughness and the dimension of the crater are connected to the current intensity but as the penetration depth increases this relationship becomes less evident. A study focused on micro EDM was conducted in [Jahan 2017] on titanium alloys in order to test the biocompatibility after EDM machining. For this type of application, to promote the cell growth around the implant, the surface finishing must be neither too high nor too low. The tests were conducted using EDM oil as dielectric. Carbon, from the decomposition of the oil at high temperatures, and oxygen from the atmosphere due to the oxidation of molten metals during the machining were found on the workpiece surface. EDX analysis confirmed the migration of the elements from the electrode on the workpiece, especially for the material having a weak alloying tendency. Microhardness measurements were also made and an increase in microhardness of the machined surface than the original one was achieved.

The workpiece material during the erosion can be modified by the migration of material from the electrode to the workpiece as well. This phenomenon is well known in literature [Soni 1996, Singh 2022, Bhattacharya 2013] and it was demonstrated that the material migration takes place in bidirectional way [Saxena 2016].

The migration can be beneficial and EDM can even be used for surface modification, as reported in [Balanou 2021] in the case of steel tools. The electrode was formed on green Cu and ZrO_2 compacted powders. The bond between powders is not as strong as the sintered electrode permitting therefore a higher wear. In this type of application, the MTR (Material Transfer Rate) was evaluated to the detriment of the MRR. In biomedical sector, the application of EDM for the surface modification to improve biocompatibility is under investigation and offers several advantages, in terms of the quality and the cost, respect the chemical processes like deposition by chemical or physical vapor or plasma electrolytic solutions [Nafi 2023].

However, the migration and deposition mechanisms have a stochastic nature considering the fact that several factors affect this phenomenon such as the process parameters and the physical characteristics of the tool and the workpiece. In the case of PM-EDM (Powder Mixed-EDM), the characteristics of the powders must be taken into account as well [Al-Amin 2021].

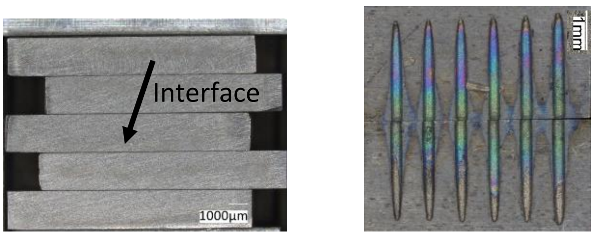
Statistical analysis on the factors affecting the migration on the workpiece surface demonstrated that only the electrical parameters are significant factors while both electrode coating and the electrode rotational speed seem to be negligible [Jahan 2019]. The same result was found for the crater size.

The type of hole (through or blind) influences the amount of migrated material from tool to workpiece. When hydrocarbon oil is used as dielectric, the dielectric can be dissociated forming carbon particles that can cover the surface with a thin black film

[Kumar 2019]. The carbon film can also be generated on the electrode surface acting as a protective layer and consequently reducing the wear rate [Supawi 2023]. The electrode wear rate, affected by the process parameters in terms of peak current and pulse on time, influences the shape of the deposited material on the electrode surface.
Flushing plays a key role in the volume of migrated materials on the workpiece. A better flushing reduces the surface defects and the process parameters, that enlarge the spark gap, reduce the migration of carbon and other materials on the workpiece surface [Jahan 2012]. In the case of micro milling, thanks to the scanning strategy adopted by the tool that improves the flushing conditions, less migration of carbon occurs than in the case of die sinking. An inverse correlation between the finishing surface and the carbon migration.
Of course, the process parameters influence in general the process and the duty factor (the ratio between the pulse on time and the cycle time) revealed to be one of the most important factors that affects the relocation of elements on tool and workpiece [Rizvi 2023].
Regarding the type of dielectric, it was found that the migration of material occurs for both pure water and EDM oil. Electrode diameter influences the surface roughness due to the skin effects but a variation on the migration seems to be negligible [Liu 2019].
In this paper the effects of the type of machining (roughing or finishing) and the effects of the washing pressure by the internal diameter of the electrode on the internal surface of the hole were investigated. The analysis was conducted by SEM images, observation of the craters size and the measurement of the surface roughness. Finally, EDS analyses on both the workpiece and the electrode tip confirmed the material migration in bidirectional way from the electrodes.

2 DESCRIPTION OF THE EXPERIMENTAL PLAN

The experimental tests were made using a Sarix (SX-200). Micro holes were made on titanium sheets using hydrocarbon oil as dielectric. In order to investigate the internal surface of the hole, two sheets were coupled and clamped using a device specifically designed for this purpose. The holes were drilled at the interface between the two workpieces. In this way, after drilling, the sheets can be separated, allowing access to the internal surface of the hole. It was necessary to estimate the equation of the interface line to define the coordinates of the holes. The equation of the interface line was obtained by a series of touch operations between the electrode and the start or end part of the sheets. Fig. 1 reports the coupling of the sheets and an example of the internal surface of the holes after the separation of the two sheets.



(a) (b)

Figure 1. Coupling of the sheets (a) and internal surface of the holes (b)

Fig. 2 shows an image of the centering result, the error of the defined procedure calculated by the distance between the center of the hole and the interface line was about some tens of micro-meters.

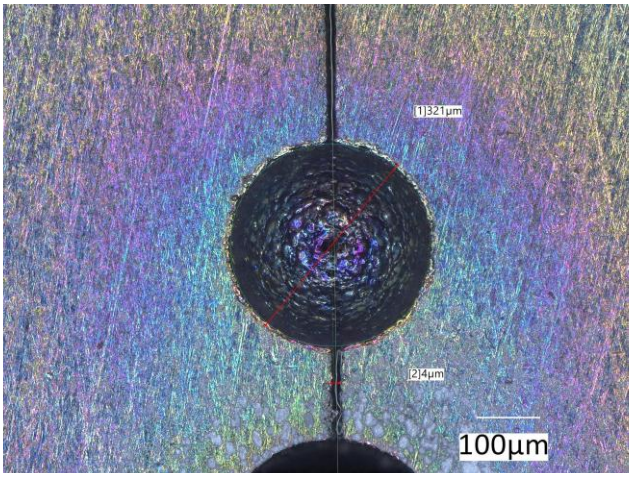


Figure 2. Measurement of the centering of the hole on the interface line between two sheets

As tool, tungsten carbide tubular electrode having an external diameter of 0.3 mm and the internal one of 0.12 mm was used. Two different sets of process parameters were adopted, one typical for roughness (R) and the other typical for finishing (F). Two internal washing pressures were tested, one for the low pressure (L, 8 bar) and the second one for high pressure (H, 40 bar). The drilling operation was made using two different operational conditions for each experimental test. In the first one, the drilling was realized in a single step while in the second one by multiple steps. The program records the machining time and the electrode wear. In the case of single step, only the total machining time and the final electrode wear are recorded. In the case of multiple steps, the drill is executed with several steps with a descent of the spindle of 0.1 mm for each of them. After each step, the electrode is sent to a control point to measure the wear. In this case, the report contains machining time and the cumulative electrode wear of each step. By the elaboration of these data, the evolution of the drilling operation can be studied.
The analysis of the internal hole surface as well as of the electrode tips was carried out by digital optical microscopy (Keyence VHX) and FE-SEM (Field Emission Scanning Electron Microscope, Zeiss Gemini 300, secondary electrons detector, 60 µm aperture) equipped with electron dispersive X-ray probe (Orford X-Act detector, 20 kV emission voltage, 10 mm working distance).
Surface analysis was carried out by optical confocal microscopy (Sensofar S-Neox microscope) by using 100X confocal lens, green LED, single region of interest (ROI), cylindric form removal Waviness S-F (S filter = 2.5 um, F filter = level plane) according to ISO 25178.

3 RESULTS AND DISCUSSION

After drilling, longitudinal sections of the holes are available by just disassembling the specimen set: an example is shown in Fig. 3, where most holes described in this report (7 out of 8, actually) are shown. Since the process does not involve mechanical polishing, it is able to preserve even very fragile details, such as the central pin left by tubular electrodes. A general idea about the holes, such as the surface texture and the bottom shape is given as well.
Another source of information originates from the “traditional” technological indexes, machining time and electrode wear. When drilling is performed in multiple steps, the evolution of such indexes is available as a function of time.

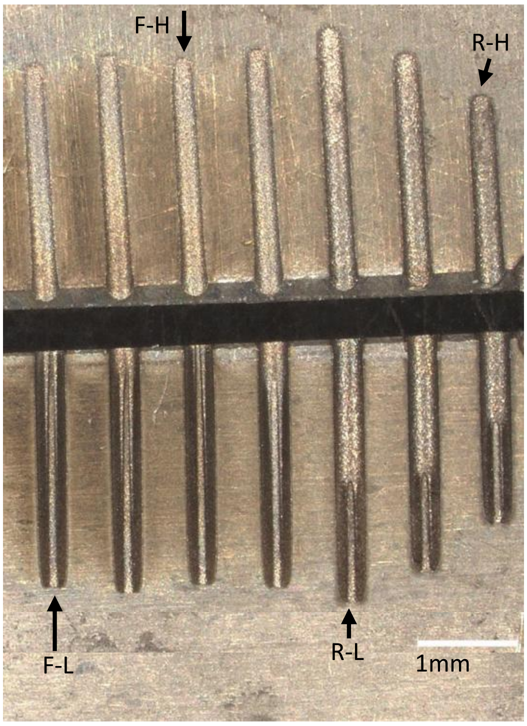


Figure 3. Internal surface of the holes

The time evolution of the hole depth (sometimes referred to as "motion law") is shown in Fig. 4. The initial part of the curves is due to non-planar entry surface (chamfers, Z-misalignment between specimen sides) and it can be assumed to be not relevant. Apart from the initial phase, in all cases machining depth is linearly dependent on time. This effect supports the assumption that the removal process is not affected by machining depth.

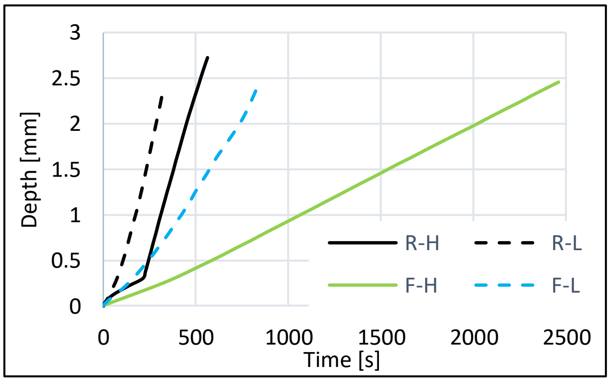


Figure 4. Motion law of the electrode during the drilling operation

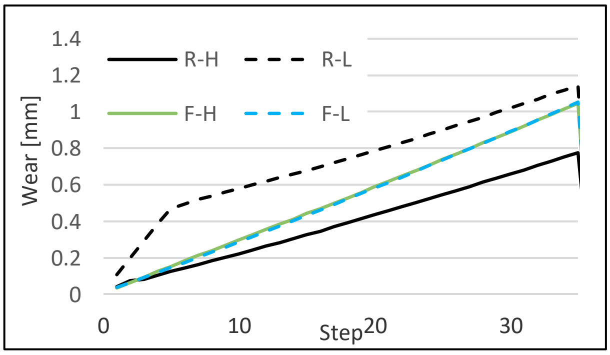
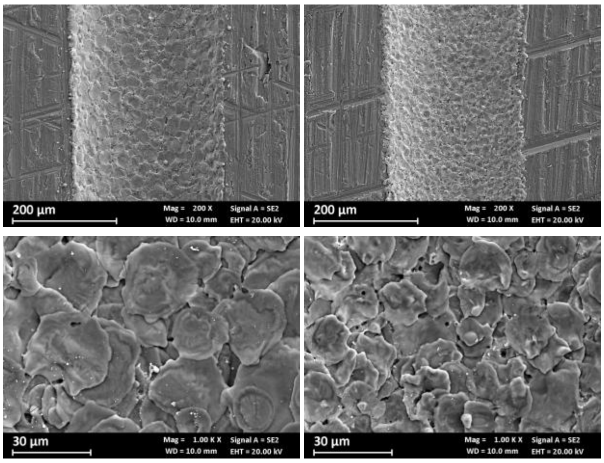
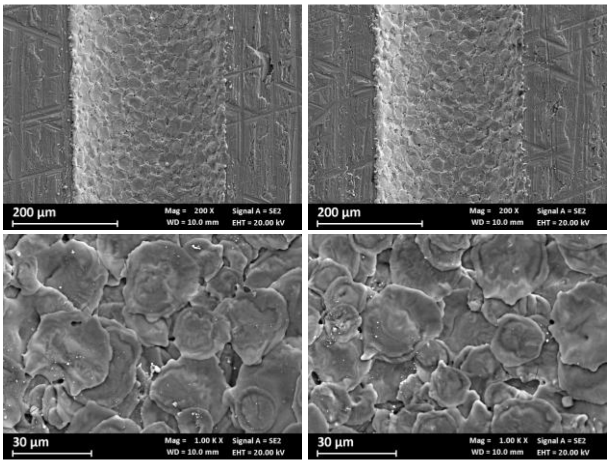


Figure 5. Cumulative electrode wear during the drilling operation



(a) (b)

Figure 6. SEM images of the internal hole, effect of the energy: R-H (a) F-H (b)



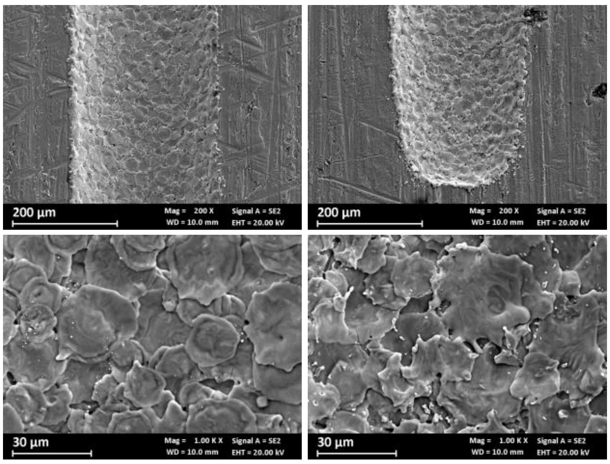
(a) (b)

Figure 7. SEM images of the internal hole, effect of the internal washing pressure: R-H (a) R-L (b)

In finishing, lower dielectric pressure allows a faster material removal rate; this effect can lead to the reasonable assumption that there is an «optimal» number of debris which affects the overall manufacturing rate. In fact, the presence of debris during the micro-EDM drilling process significantly influences the electrode's penetration behavior into the workpiece. When excessive debris accumulates in the machining zone, frequent short circuits occur, leading to a reduction in MRR. Conversely, an overly clean dielectric fluid can delay the onset of electric discharges, also hindering the efficiency of the process. This suggests the existence of an optimal debris concentration, which corresponds to the maximum Z-axis velocity of the electrode. Before to reach this optimal level, the increasing debris concentration enhances the machining rate. However, once this threshold is surpassed, the surplus of debris destabilizes the process, causing a slowdown in machining. The time required to reach this optimal debris concentration depends on several factors, including electrode type and length, the process parameters and the flushing of the dielectric fluid.

Pressure is supposed to affect the processing rate, but its effect is complex and further investigations are needed to better understand the role of the debris removal mechanism on the process performance. Machining performance decreases during flushing at higher pressure due to the low presence of debris in the machining area. At the moment, a positive correlation between debris amount and process rate is supposed in the explored technological window. When roughing, the slope of

either curve (H and L) is very similar. In this case, the debris production is faster and their concentration does not exit from its optimal range.
A linear dependence is displayed also in Fig. 5, reporting electrode wear evolution. In this case, roughing parameters yield a lower wear while no effect of flushing pressure is evident.
FE-SEM analysis of the hole surfaces is reported. Different images are compared to show the effect of machining conditions. Fig. 6 compares different spark energies, typical of roughing (R) and of finishing (F). Differences in texture are visible, especially related to different spatter sizes. A similar result is displayed when changing the internal flushing pressure. The effect of flushing pressure on craters morphology is shown in Fig. 7. In this case, no remarkable effect can be detected, as expected.
Details of the hole surface, taken at different hole depths, are shown in Fig. 8. In this case, although the spatter size does not appear to change, the shape of the craters becomes less regular towards the hole bottom. This can be ascribed to the inhomogeneous distribution of the sparks at the electrode tip and the consequent re-deposition of the material in the final zone of the hole also affected by the flushing.



(a) (b)

Figure 8. SEM images of the internal hole for the case R-L in two zones: middle zone (a), bottom zone (b)

Fig. 9 shows surface data, as collected through the optical profilometer. Surface roughness data may be gathered and compared; they are reported in Tab. 1. As expected, finishing produces smoother surfaces. Negligible effects of flushing pressure can be noticed, as confirmed also by morphological considerations.

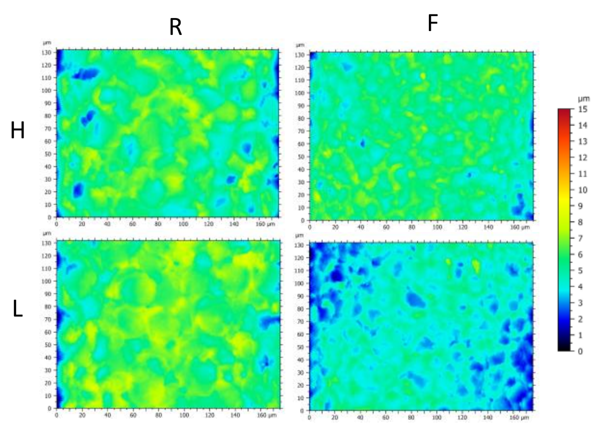
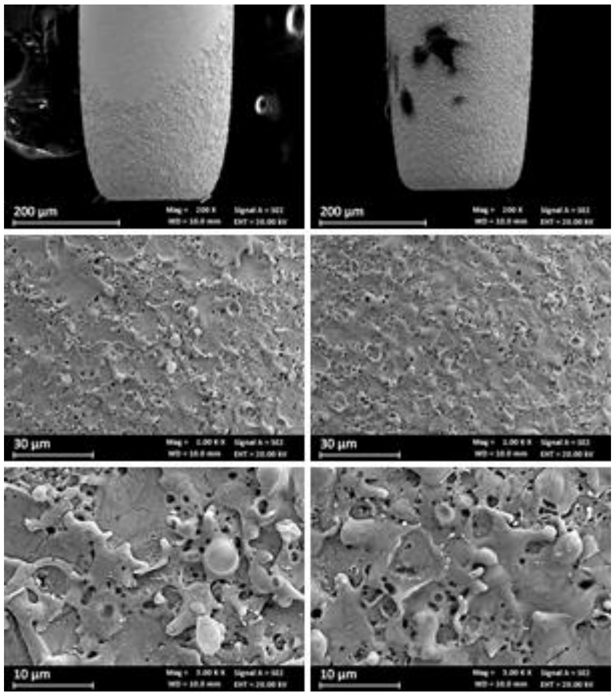


Figure 9. Map of the surface roughness

	R	F
H	0.74	0.48
L	0.58	0.44

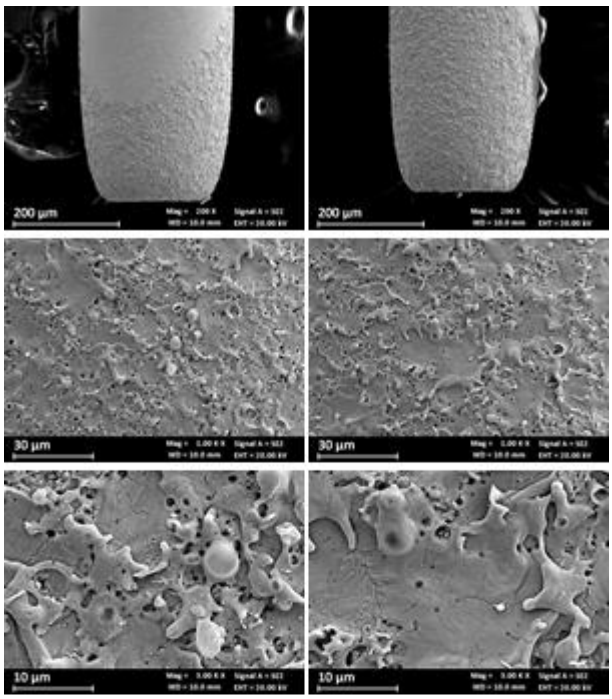
Table 1. Surface roughness (Sa, ISO 25178) for the different conditions, expressed in µm

SEM images of the electrode tip after machining are reported in Fig. 10 and Fig. 11. The effects of the process parameters on the spatter size for the electrode tip are more evident, while the effects of the washing pressure are not evident.



(a) (b)

Figure 10. SEM images of the electrode tip after machining, effect of the energy: R-H (a) F-H (b)



(a) (b)

Figure 11. SEM images of the electrode tip after machining, effect of the internal washing pressure: R-H (a) R-L (b)

Finally, Fig. 12 reports the results of EDS analysis on both the holes and the electrode tips. Tungsten carbide was found on the hole surfaces while titanium was found on the electrode tip. A relationship between the type of process parameters (Roughing and Finishing) and the migration of the material. from the workpiece and the electrode and vice versa, was found for both the flushing pressures. Concerning the workpiece, the weight % of tungsten carbide (W) is higher in finishing compared to roughing and exactly the opposite was found at the electrode tip, where the percentage of titanium (Ti) is higher for roughing. The type of machining affects the crater size and the debris size is affected, as a consequence. Thanks to the high solubility of W in Ti, the formation of intermetals is rather favored by the huge number of Ti-rich debris produced during the roughing compared to finishing. This tends to increase the Ti availability at the electrode side during this phase. The Ti-W intermetallic formation at the electrode is then favored, as a consequence. The higher the amount of titanium deposited at the electrode, the lower the W deposition at the workpiece is then expected. In the case of finishing, W enrichment occurs at the hole side. The flushing effect is even negligible, but appears to be more evident in roughing, thus confirming the hypothesized deposition mechanism. The higher the pressure, the higher the amount of titanium deposited at the electrode and the lower the tungsten that is transferred to the workpiece.

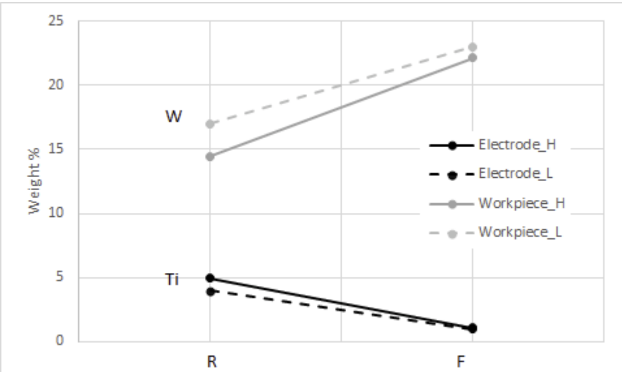


Figure 12. Material migration on electrode and workpiece as a function of machining parameters (R-F) varying the washing pressure (H-L)

4 CONCLUSIONS

The effects of the type of machining (roughing or finishing) and the effects of the flushing pressure (high and low), through the internal diameter of the electrode, on the internal surface of the hole realized by micro-EDM were investigated. The study of the time evolution of the hole depth showed that the removal process is not affected by the machining depth. Both the process parameters and the flushing pressure of the dielectric have effects on the machining rate. The role of the debris, their concentration into the dielectric and the debris removal mechanism are aspects that should be better investigated. FE-SEM analysis of the hole surfaces shows differences in texture between roughing and finishing while the effects of the washing pressure is less evident. Surface roughness data confirmed this result. A relationship between the type of machining and the migration of the material, from workpiece and electrode and vice versa, was found. A deposition mechanism of material has been hypothesized based on the formation of an intermetallic compound which should hinder the tungsten transfer to the workpiece. This effect has to be confirmed by further targeted experimental campaigns. EDS analyses will be performed at different depths of the hole and on various zones of the electrode under all tested conditions. Additionally, the debris solidified in the dielectric fluid will be collected and analyzed to gain further insights into the chemical compounds formed during the process.

REFERENCES

[Al-Amin 2021] Al-Amin, M., et al. Investigation of Coatings, Corrosion and Wear Characteristics of Machined Biomaterials through Hydroxyapatite Mixed-EDM Process: A Review. *Materials*, 2021, Vol.14, No.13, pp 3597. https://doi.org/10.3390/ma14133597

[Balanou 2021] Balanou, M., et al Investigation of Surface Modification of 60CrMoV18-5 Steel by EDM with Cu-ZrO_2 Powder Metallurgy Green Compact Electrode. Machines, 2021, Vol.9, No.11, pp268. https://doi.org/10.3390/machines9110268

[Bhattacharya 2013] Bhattacharya, A., et al. Surface characterization and material migration during surface modification of die steels with silicon, graphite and tungsten powder in EDM process. J Mech Sci Technol, 2013, Vol.27, pp 133–140. https://doi.org/10.1007/s12206-012-0883-8

[Choudhary 2014] Choudhary, S.K., Jadoun, R.S. Current advanced research development of electric discharge machining (EDM): a review. International Journal of Research in Advent Technology, 2014, Vol.2, No.3, pp 273-297.

[Fard 2025] Fard, M.G., et al. Towards sustainable precision: A review of water jet meso and micromachining. Results in Engineering, 2025, Vol.27, 106447. https://doi.org/10.1016/j.rineng.2025.106447

[Jahan 2012] Jahan, M.P., et al. Study of the Diffusion of Carbon, Its Sources, and Effect on Finishing Micro-EDM Performance of Cemented Carbide. J. of Materi Eng and Perform, 2012, Vol.21, pp 1655–1668. https://doi.org/10.1007/s11665-011-0083-1

[Jahan 2017] Jahan, M.P., et al. Comparative Study on Micro-electro-discharge-machined Surface Characteristics of Ni-Ti and Ti-6Al-4V with Respect to Biocompatibility. Procedia Manufacturing, 2017, Vol.10, pp 232-242. ISSN 2351-9789. https://doi.org/10.1016/j.promfg.2017.07.051.

[Jahan 2019] Jahan, M.P., Alavi, F. A Study on the Surface Composition and Migration of Materials and Their Effect on Surface Microhardness during Micro-EDM of Ti-6Al-4V. J. of Materi Eng and Perform, 2019, Vol.28, pp 3517–3530. https://doi.org/10.1007/s11665-019-04120-0

[Jaware 2015] Jaware, V.B., Takale, A.M. Review on EDM and Wire-EDM machining of TiNi Shape Memory Alloys. International Journal of Engineering Technology, Management and Applied Sciences, 2015, Vol.3, pp 99–108.

[Kumar 2019] Kumar, M., et al. Electro-discharge Machining Performance of Ti–6Al–4V Alloy: Studies on Parametric Effect and Phenomenon of Electrode Wear. Arab J Sci Eng, 2019, Vol.44, pp 1553–1568. https://doi.org/10.1007/s13369-018-3632-1

[Liu 2019] Liu, Q., etv al. Surface Integrity of Micro EDM Surface Using Electrodes of Various Diameters. *Coatings,* 2019, Vol.9, No.12, pp 805. https://doi.org/10.3390/coatings9120805

[Mascaraque-Ramirez 2015] Mascaraque-Ramirez, C., Franco, P. Experimental Study of Surface Finish During Electro-Discharge Machining of Stainless Steel. Procedia Engineering, 2015, Vol.132, pp 679-685. ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2015.12.547.

[Nafi 2023] Nafi, M.A., Jahan, M.P. Functional Surface Generation by EDM—A Review. Micromachines, 2023, Vol. 14, No,1, pp 115. https://doi.org/10.3390/mi14010115

[Rizvi 2023] Rizvi, S.A.H., Agarwal, S. Migration of Electrode Material During Electro Discharge Machining. Natl. Acad. Sci. Lett., 2023, Vol.46, pp 333–335. https://doi.org/10.1007/s40009-023-01254-7

[Saxena 2016] Krishna Kumar Saxena, et al. Surface Characterization, Material Removal Mechanism and Material Migration Study of Micro EDM Process on Conductive SiC. Procedia CIRP, 2016, Vol.42, pp 179-184. ISSN 2212-8271. https://doi.org/10.1016/j.procir.2016.02.267

[Singh 2022] Singh, M., Singh, S. Comparative Capabilities of Conventional and Ultrasonic-Assisted-Electrical Discharge Machining of Nimonic Alloy 75. J. of Materi Eng and Perform, 2022, Vol.31, pp 4611–4623. https://doi.org/10.1007/s11665-022-06601-1

[Soni 1996] Soni, J.S., Chakraverti, G. Experimental investigation on migration of material during EDM of die steel (T215 Cr12). Journal of Materials Processing Technology, 1996, Vol.56, No.1–4, pp 439-451. ISSN 0924-0136. https://doi.org/10.1016/0924-0136(95)01858-1

[Supawi 2023] Supawi, A., et al. Electrode Wear Rate of RBD Palm Oil as Dielectric Fluids on Electrical Discharge Machining (EDM) at Different Peak Current and Pulse Duration of Titanium Alloys. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 2023, Vol.112, No.2, pp 54–63. https://doi.org/10.37934/arfmts.112.2.5463

[Tiwary 2018] Tiwary, A.P., et al. Investigation on the effect of dielectrics during micro-electro-discharge machining of Ti-6Al-4V. International Journal of Advanced Manufacturing Technology, 2018, Vol.95, pp 861–874. https://doi.org/10.1007/s00170-017-1231-z

[Tsai 2004] Tsai, Y.Y. and Masuzawa, T. An index to evaluate the wear resistance of the electrode in micro-EDM. Journal of Materials Processing Technology, 2004, Vol.149, No.1–3, pp 304-309. ISSN 0924-0136. https://doi.org/10.1016/j.jmatprotec.2004.02.043

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