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# Wear measurement of rotational tool of hard metal and tungsten to produce microholes with the ECDM-machining process using relaxation generator

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## Abstract:

This work aims to experimentally investigate the influence of rotational velocity of the tool-electrode (with diameter of 110 µm), varied within defined limits, on the tool wear (tool-electrode wear), producing microholes using the electro chemical discharge machining (ECDM). Two different materials of tool-electrodes were used to perform these experiments: hard metal and tungsten. In other words, for each one of these electrically conductive materials, the tool-electrode movement has been modified in 20, 1000 and 2000 RPM using a tool-machine AGIE Compact 1, electronically and mechanically adapted to the ECDM-machining process to produce holes with small diameters. As working medium of the ECDM-technology a passivating electrolyte solution of $Na_2SO_4$ with extremely low conductivity in mS/cm was applied to machine holes in stainless plates with a thickness of 0,6 mm as workpiece material. The experimental results shown significant differences related to the tool-electrode wear being investigated for the rotation levels indicated above. These results are explained in the paper in terms of physical properties of the tool-electrode materials and, mainly, based on electronical characteristics of the power supply (a relaxation generator) of the machine AGIE that controls the total energy of the ECDM-pulses directly responsible for the material removal of the microhole being machined and, consequently, for the generation of debris in the working gap during the machining process. Finally, this article also gives an extremely important technological contribution for the future development of specific generators of high performance to achieve the best work results applying the ECDM-machining, tanking into account the movement characteristics of the tool-electrode penetrating into the workpiece being machined.

**Keywords:** Electro chemical discharge machining, ECDM, microhole, tool-electrode wear, electrolyte, $Na_2SO_4$, relaxation generator

## 1. Introduction

Hard metal and tungsten are two important materials of tool-electrode used to produce holes with small diameters in steels through the electrical discharge machining (EDM). Because this application, these materials also gain a special consideration in case of machining process of microholes with the use of the electro chemical discharge machining (ECDM), since this combined technology (EDM and ECM acting together) is currently a new manufacturing process with specific applications, for example, in the automobile industry to produce injection components. Normally it is desired in the practice that the tool-electrode materials present a low wear and also have a high mechanical stiffness during the ECDM-machining process, what makes it possible to machine holes with precise geometry and thus to reduce production costs through the assurance of a manufacturing process with high quality of machined parts.

Both electrically conductive materials (HM and Wo) have physical properties (**table 1**) which can satisfy these machining requirements and certainly should be used with optimum adjustment conditions of the ECDM-machine generator to avoid problems in

| | Hard metal (HM) | Tungsten (Wo) |
|---|---|---|
| **Melting point** | ~ 2720 °C | 3422 °C |
| **Density** | ~ 15 $g.cm^{-3}$ | 19,25 $g.cm^{-3}$ |
| **Boiling point** | Not available | 5930 °C |
| **Heat of fusion** | Not available | 35,3 $kJ \cdot mol^{-1}$ |
| **Heat of vaporization** | Not available | 774 $kJ \cdot mol^{-1}$ |
| **Thermal conductivity** | ~ 100 $W \cdot m^{-1} \cdot K^{-1}$ | 173 $W \cdot m^{-1} \cdot K^{-1}$ |
| **Thermal expansion** | ~ 7,5 $10^{-6}$ $K^{-1}$ | (25 °C) 4.5 $\mu m \cdot m^{-1} \cdot K^{-1}$ |
| **Electrical resistivity** | Not available | (20 °C) 52.8 $n\Omega \cdot m$ |
| **Young's modulus** | ~ 600 GPa | 411 GPa |

**Table 1:** Most important physical properties of hard metal [1] and tungsten

the working gap during the machining process of a microhole, as for example here, a strong passivation of the metallic surface of the tool-electrode or workpiece leading to a total hindrance of the material removal procedure. Furthermore, beyond the aspects “costs and hole geometry” described above, a tool-electrode material has a very high importance for surface quality of a machined hole, mainly because this can microscopically influence the surface roughness and thermally influenced zone in the hole through a material transfer tool-electrode/workpiece during the machining process, occurring in the plasma channel between these electrodes developed within the EDM-phase of the ECDM-process. Here, for example, the superficial condition of machined holes in injection systems has an important contribution for a perfect limitation of the emission grade and fuel consumption of a motor. These facts make it possible to evidence the significance of the realization of experiments with ECDM-process to correctly define the tool-electrode material for a mechanical part with specific application, and also taking into account the aspects related to production costs of the machining process. The experiments presented in the sequence of this paper aim to investigate the behavior of the wear of tool-electrode composed of tungsten or hard metal, using different levels of tool-electrode rotations, where here a tool-machine of the manufacturer AGIE Charmilles and a special methodology of design of experiments (DOE) were used, applying only a chemical composition of electrolyte solution as working medium of the ECDM-machining process. For example, the closed-loop control system of this machine, working together with a particular adjustment of ECDM-process parameters, is fundamental for assuring a reduced level of tool-electrode wear through a perfect control of the quantity of short circuits produced during hole machining as well as by helping to maintain the exact distance of working gap and, finally, to determine the total energy of the process phases within the ECDM-pulses produced with the machine generator. In the case of the experiments of this work, the rotational tool movement has direct influence on the output variables of these pulses (electric current and time of the phases ECM and EDM of ECDM-pulse) controlled in specific frequency, thus leading to effects on the tool-electrode wear with defined intensity. Modifications of this frequency, set up by the total time between ECDM-pulses, conduct to profound alterations of this wear (in dependence on the tool-electrode material) and of the material removal rate of the hole being machined. In the experiments of this work, for a better interpretation of the experimental results, this time (normally adjusted in µsec by some electronic functions of the machine generator) has not been modified to machine microholes.

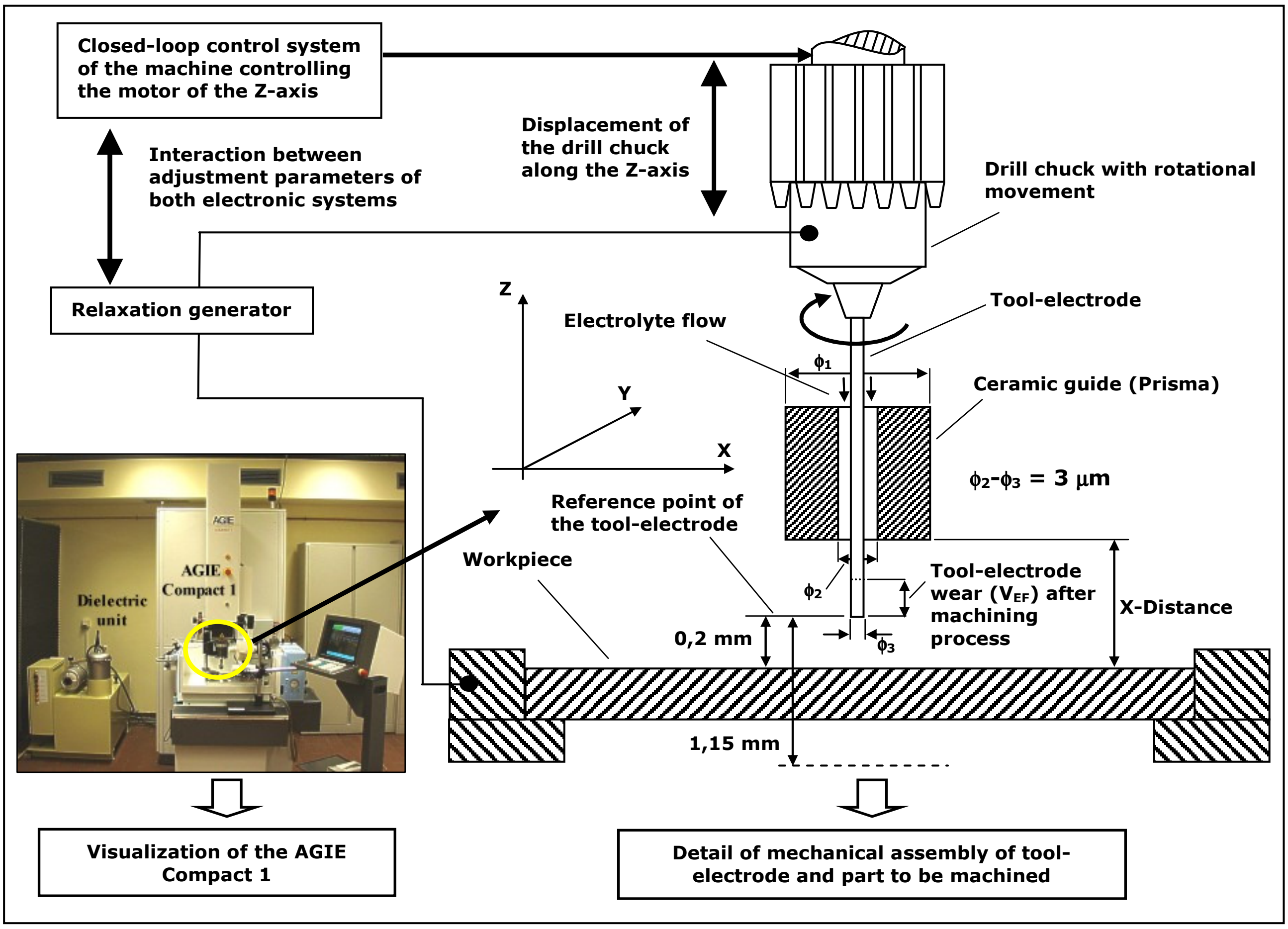

**Figure 1:** Machine AGIE Compact 1 used in the experiments

## 2. Experimental methodology

The experiments has being performed with the machine of the manufacturer AGIE Charmilles, model AGIE Compact 1 (**figure 1**). This equipment was mechanically and electronically adapted to work with the ECDM-technology, that is, to enable the machining process of microholes using a passivating electrolyte as working medium instead of a dielectric. The mechanical modification of this tool-machine has consisted of a precise adaptation in the tool clamping system assembled at the machine Z-axis, whereas the electronic alteration of the AGIE has been made in the closed-loop control system, so that this equipment can tolerate a larger amount of electric short circuits during the ECDM-machine as consequence of the electrical conductivity of the electrolyte. Originally this machine model was projected to machine parts with larger dimensions through the EDM-sinking process using deionized water with low conductivity (precisely controlled by the "dielectric unit") in the working gap. Furthermore, in the case of the ECDM-process using the AGIE Compact 1, the working medium was conducted into the gap between electrodes through a "peristaltic pump" of the company IKA, correspondently adapted to this machine for working with electrolyte, totally replacing the original hydraulic unit of the dielectric. In the experiments of this work, the electrolyte solution undergoes a small conductivity increase and is intensively contaminated with the products removal, being subsequently discarded after the machining process. The total temperature of this medium was adjusted approximately between 25 – 30 °C.

**Table 2:** Experimental planning

| NON-VARIABLE PARAMETERS | DESCRIPTION |
|---|---|
| ❒ Tool-electrode diameter | Bar with diameter of 0,1 mm (for hard metal and tungsten) |
| ❒ Workpiece | Plate of stainless steel with thickness of 0,6 mm |
| ❒ Electric voltage at the electrodes ($u_{ECDM}$) | 150 Volt |
| ❒ Electrolyte volume | 0,9 ml/s (laterally applied at the tool-electrode) |
| ❒ Max. machining depth | -1,15 mm |
| ❒ Electrolyte solution | Sodium sulfate ($Na_2SO_4$) |
| ❒ Electrolyte conductivity | 0,25 m/S |
| ❒ Capacitance of the capacitor | 25 nF |
| **VARIABLE FACTORS** | **DESCRIPTION** |
| ❒ Material of the tool-electrode | Hard metal and tungsten |
| ❒ Tool-electrode rotation | 100, 1000 and 2000 RPM |

**Table 2** shows the main process parameters that has been modified (variable factors) during the realization of experiments. Here, the material of tool-electrode and tool-electrode rotation were varied respectively in two and three levels, so that the experimental interaction between these parameters was determined through analysis of variance ("Two-Way ANOVA"). For both parameters, a group of non-variable parameters was defined to machine microhole in stainless steel plates using the ECDM-process. In this case, the use of a passivating electrolyte solution ($Na_2SO_4$) is very important to produce holes with a good surface roughness and high dimensional precision, due to the formation of passive layers on the hole's surface during the machining process. This solution is a chemical mixture between deionized water with extremely low electrical conductivity (< 0,5 mS/cm) and sodium sulfate in powder form. The solution volume was applied into the working gap in 0,9 ml/s, where this medium has the task to remove the removal products out of the machining zone, so that there short circuits can be avoided for the optimal process performance. Some experiments with the ECDM-technology has demonstrated that the use of a very high volume of electrolyte normally leads to a rapid debris removal from the small space between electrodes, but, on the other hand, provokes in some cases a difficulty to generate ECDM-pulses with the exact time related to the phases ECM and EDM, which are necessary to the correct material removal of the workpiece being machined as well as to minimize the tool-electrode wear. A high electrolyte flow in the working gap tends to the non-development of a complete electrical isolation in the frontal working

gap (through the gas amount $H_2$ produced by electrochemical reactions during the ECM-phase) for the initialization of an electric spark (start of the EDM-phase of the ECDM-process) in the middle of the tool-electrode and workpiece. In other words, for each group of non-variable input parameters of the ECDM-machining an optimal adjustment of electrolyte volume must be done for the perfect development of the process phases, to further improve the machining conditions.

Since the experiments have as main objective a precise evaluation of the tool-electrode wear, an exact measurement method of this output variable, dependently on the variation of the input parameters being investigated, must be applied. Basically, having here as reference the **figure 1**, before the start of machining process, the tool-electrode is adjusted at a distance of 0,2 mm from the workpiece surface ("reference point") to be machined. After the initialization command to start the machining process, the tool reaches a maximum machining depth of -1,15 mm, returning back to the reference point, where in this case a tool wear can be verified. To measure this wear, a workpiece displacement firstly takes place within the plane XY of the tool-machine. In the sequence, a tool-electrode movement manually occurs (using the open-loop controller of the AGIE machine) until a mechanical contact with the workpiece. The total distance traveled by the electrode until to this contact point, minus the value of 0,2 mm, is defined as the total tool wear presented in the next chapter of this paper. This tool wear is expected to be different according to the tool-electrode materials being analyzed due to their differences in physical properties, as indicated in the **table 2**. Some of the material properties indicated in this table (melting point, boiling point, heat of fusion and vaporization as well as thermal conductivity) normally have a high importance in limiting the melting volume of the tool-electrode in the EDM-phase of the ECDM-pulse as consequence of the high temperatures achieved here, directly influencing the tool-electrode wear. These temperatures are produced by the plasma channel (with very high thermal content) formed during this phase as effect of ionization phenomena immediately after the end of the ECM-phase. In the case of the experiments of this work, the ionization of the EDM-phase takes place with the negative polarization of the tool-electrode adjusted by the relaxation generator of the tool-machine, what certain has an influence on the wear being experimentally investigated. Furthermore, especially in the case of the hard metal, the composition of the material phases (% WC and % Co) [2] is an important characteristic to determine the tool wear intensity in dependence on the ECDM process parameters. Both phases have different physical properties of thermal conductivity, that is, the energetic content produced during an electric spark (EDM-phase) differently flows in the tool-electrode material through the WC and Co. The combination of these chemical elements in different proportions defines the respective capacity of thermal flow of the HM with direct influence on the tool wear. Beyond this, it is should be also bear in mind that the porosity grade of this material type, in dependence upon the technology of hard metal processing by powder metallurgy, can have important influences on the electrode wear during the ECDM machining process of a microhole. In some cases, the presence of other phase components, beyond tungsten carbide and cobalt, in the chemical composition of the hard metal can also be advantageous for improving this work result of the ECDM-technology, that is, the reduction of tool wear in defined limit. The introduction of these components in the material should not affect the material's Young's modulus, thus avoiding any a decrease of geometrical precision of the machined hole. A high value of Young's modulus also avoids an excessive tool-electrode vibration during machining process.

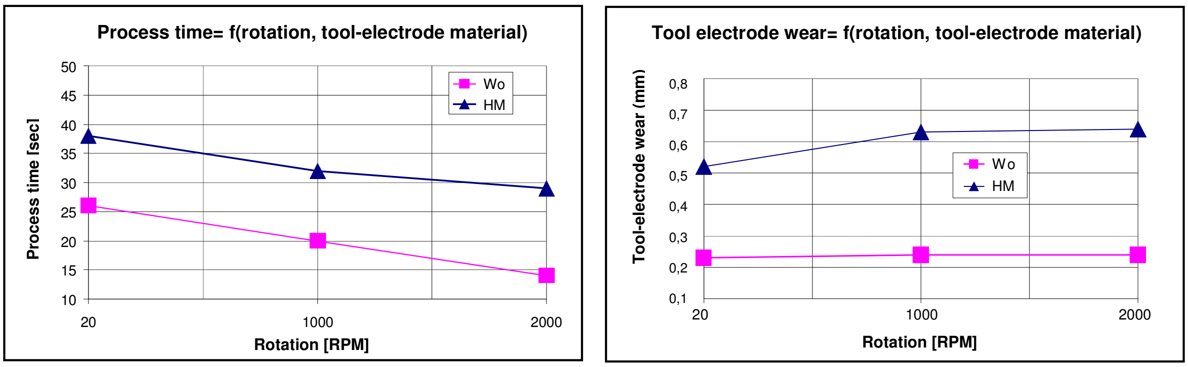

**Figure 2:** Analysis of tool-electrode wear for hard metal and tungsten

## 3. Results and discussions

**Fig. 2** presents the results referred to the experimental planning of **table 2**. Significant differences between the materials being studied for the tool-electrode wear were found. In the practice, during the realization of the experiments, the ECDM-machining process of tungsten was possible within the whole variation field of tool-electrode rotation. The machining with HM could be done only with application of the rotation in 20 RPM. For higher rotations, the tool-electrode suffers an extreme glowing, leading to a total impediment of the machining procedure. The RPM increase has consequence a strong elevation of temperature within the working gap and, together with the generation of gas $O_2$, tends to provoke a strong passivation on the tool-electrode surface, thus causing here a strong increase of high electrical resistance to the current flow between the electrodes. This passivity effect is also the direct result of the "shape" of electric current during the EDM-phase of the ECDM-process. During this phase, there is constantly an alternation of the tool-electrode polarity (see **figure 3**) because the constructive characteristics of the generator of the tool-machine AGIE Compact 1. When the tool is positively polarized, the development of electrochemical reactions occurs on the external surface of the tool-electrode, what conducts to the formation of oxygen gas (**eq. 1**). This chemical reaction takes place in a voltage level approximately of 25 Volts (voltage of the plasma channel formed as consequence of the electric discharge during the EDM-phase) acting at the electrodes. A second important reaction occurring in the same time (**eq. 2**) is the combination of $O_2$ (g) with cobalt of the hard metal, developing an oxide (material passivation) with low electrical conductivity (especially in this case, possibly two chemical compositions of oxides can be developed, that is, CoO or $Co_3O_4$). The passivation is certainly favored by the high temperatures achieved in the working gap during the ECDM process. This oxide formation can not be verified using

$$2H_2O + Na_2SO_4 \rightarrow 2H_2(g) + O_2(g) + 2Na^+ + SO_4^{-2} \qquad \textbf{(eq. 1)}$$

$$2Co + O_2 \rightarrow 2CoO \qquad \textbf{(eq. 2)}$$

or

$$2Co_3O_4 \leftrightarrow 6CoO + O_2 \text{ (at temperatures between 600 and 700 °C)}$$

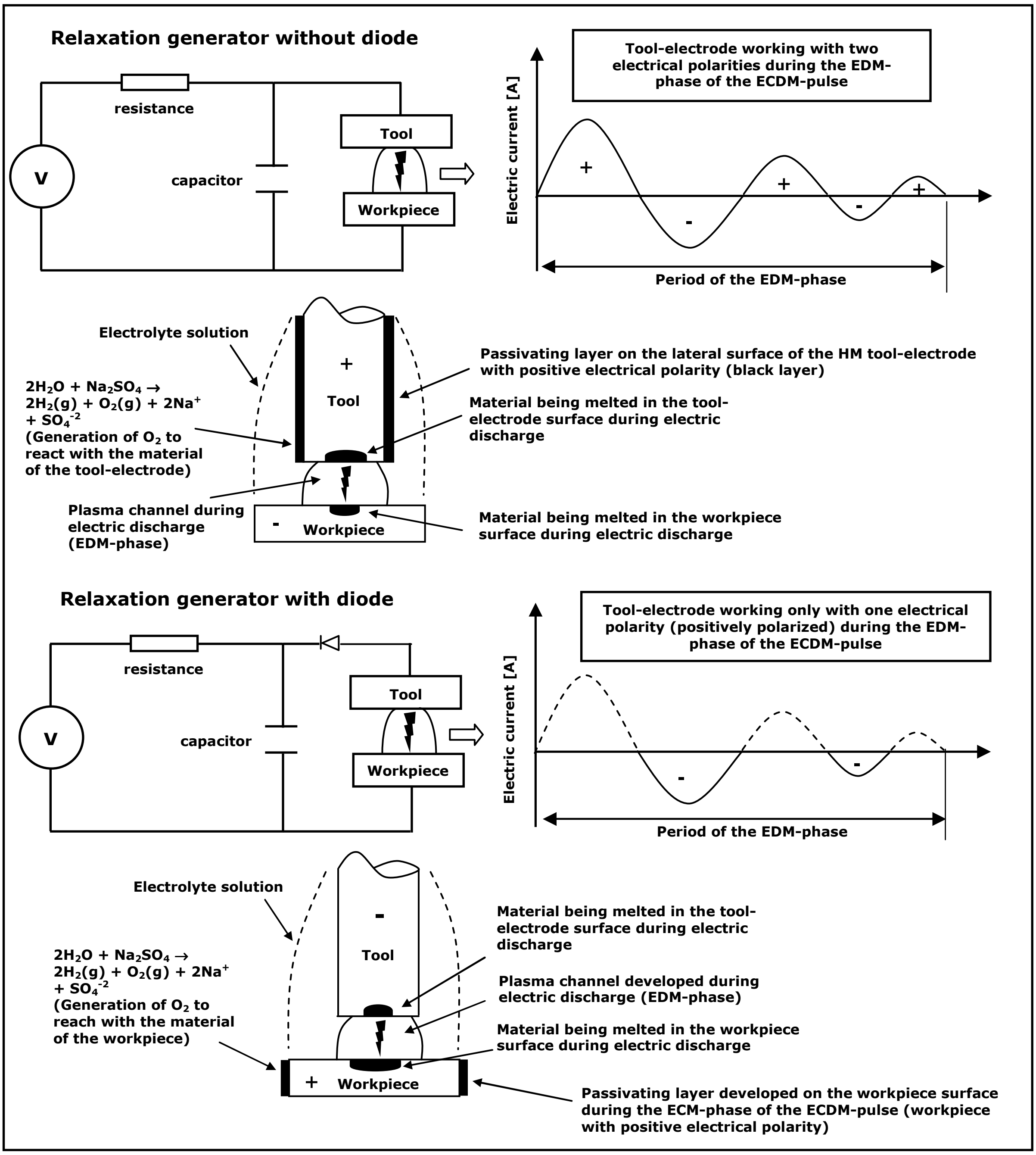

**Figure 3:** Modification of tool-electrode polarity (without diode) during the EDM-phase

tool-material chemically consisted only of Wo, where here the ECDM machining process takes place very rapid and without interruptions. In one of the graphics of the **figure 3** it can be observed that increasing the tool-electrode rotation a decrease of the process time to machine a microhole occurs. The rotation increase has a consequence a better elimination of machining products from the gap between electrodes, consequently avoiding short circuits during the hole's machining process, what reduces the number of interventions by the closed loop-control system of the EDM-machine. High rotations also lead to an enlargement of the total time of the EDM-phase available for machining (**figure 4**) and, together with good flushing condition of debris, make it possible to increase the material removal rate of the ECDM-process through the mechanism of thermal removal. Extremely high values of tool rotation has as consequence a strong temperature elevation of the gas vapors in the work medium, causing in some cases a considerable reduction of the ECM-phase of the ECDM-process. This technical condition is not feasible for the ECDM because the decrease of the electrochemical machining at the microhole surface, also increasing the probability for developing electric sparks between the lateral surface of the tool-electrode and the hole surface. To achieve the best results with the ECDM-process (low hole roughness with reduced thermal stresses, optimized machining time and minimized tool-electrode wear), it is necessary to combine during the machining process a correct intensity of ECM and EDM material removal in the frontal gap, together only with the presence of an ECM removal in the lateral space between electrodes. The geometrical characteristics of the machined hole also depend on these process phases, but also, on the mechanic adjustments of the tool-machine and mechanical properties of the tool-electrode.

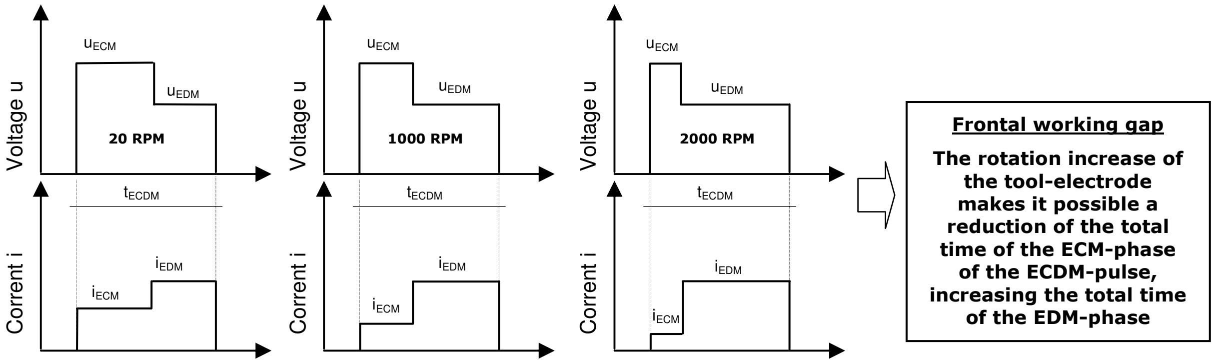

**Figure 4:** Influence of the tool-electrode rotation on the total time of the EDM-phase

## 4. Conclusions

The use of hard metal as tool-electrode material for the ECDM process is conditioned to the application of a correct electrical polarity of the tool during the machining, to avoid a passivation of the tool-electrode surface because the chemical composition of HM. This implies the utilization of special electronic components in the electrical circuit of the generator of the tool-machine, so that tool-electrode polarity always remains “negative” during the machining process. The passivity effect of HM has been explained in this article is a probable consequence of the presence of cobalt in its chemical composition. The passivation problem might be also due to the present of other chemical elements in the HM normally used to improve its mechanical properties. According to the technical conditions of the sintering process of the hard metal (for example, pressure and temperature), and with the presence of these elements, specific material phases forms as microstructural constituent of the hard metal and that may have direct effects on the performance of the ECDM machining process. Moreover, avoiding the problem related to the passivation described previously, the principal advantage of HM is its high mechanical stiffness, what usually improves the geometrical quality of the machined hole, mainly using tool-electrode with very small diameter (for hole diameter smaller as 200 µm), whereas the tungsten as tool-electrode material normally presents some problems due to excessive mechanical vibration during machining. Furthermore, independently on the types of tool materials, the application of a tool-electrode rotation makes it possible to machine small holes with a reduced process time, because the better flushing conditions of the working medium within the space between electrodes, leading to a more stable machining process. Here, specific experimental investigations can be conducted in future works to analysis how the rotation modifies the characteristics of the phases EDM and ECM of the ECDM process, taking in account, for example, the use of different generators of the ECDM-machine or also the utilization of other types of electrolytic solutions. Certainly the experimental results can be exactly analyzed in terms of machining time, surface roughness and hole diameter.

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