Analyzing machining time, geometric form and tool-electrode wear as work result of the ECDM-process producing microholes in stainless steel

Autor: Alexandre de Souza, desouza.alexandre@bol.com.br
AS INGPEED (Development in Engineering)
Blumenau-SC, Brazil

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Abstract:

This paper presents an experimental study related to the production of microholes with use of the ECDM-technology (electro chemical discharge machining), applying here adequate conditions of experiments to analyze the work result after the machining process (machining time, external diameter of holes and tool-electrode wear). These produced holes have diameters smaller as 200 µm, according to the adjusting of ECDM-parameters as well as of the dimensional characteristics of the tool-electrode. Fundamentally, in the experimental investigations of this article, the influence of the ECDM-prozess parameters (chemical composition of the electrolyte solution, electrolyte conductivity, rotational velocity of tool-electrode and total energy of the electric discharge adjusted through a capacitance of the electrical generator of the tool-machining) was verified on the above mentioned output variables of the ECDM-machining, where in this case stainless steel has been applied as workpiece material to be machined. The experiments' results indicate a strong effect of these input-variables on the work result as consequence of profound alterations of the characteristics of material removal of the machining process. This removal substantially depends of the energetic content of the phases EDM (electrical discharge machining) and ECM (electrochemical machining) of the ECDM-technology, dependently on the correspondent adjusting level of an input-variable to machine a microhole.

Keywords: Electro chemical discharge machining, ECDM, microhole, tool-electrode wear, electrolyte, NaCl, Na_2SO_4

1. Introduction

The ECDM-machining is a new manufacturing technology used today in the metal-mechanical industry to produce microcavities in electrically conductive materials, such as the austenitic, martensitic and ferritic steels. Certainly a very important application of the ECDM-technology is the machining of microholes in mechanical components with specific applications of engineering. During the ECDM-process of microhole a material removal of the workpiece being machined takes place through electric discharge (EDM) and electrochemical phenomena (ECM), what normally enables in the practice a high material removal rate of the workpiece material. This combined machining process (ECDM) is characterized in its work result by a reduced machining time and low surface roughness of the produced microhole. These output-variables are influenced by different types of ECDM process parameters, as schematically visualized in the **fig.1**. The respective adjusting conditions of such parameters determine the technical effectiveness of the ECDM-machining related to the production process of holes with extremely small diameters, as in the specific case of the experiments presented in this paper using experimental design ("design of experiments- DOE") for exactly controlling the parameters being studied within established variation fields. The correct definition of the variables' combination through these statistically planned experiments is responsible for the corresponding success of the experimental results of the ECDM-technology. For achieving this objective, a profound knowledge of the manufacturing process “electrical discharge machining” (EDM) as well as “electrochemical machining” (ECDM) is firstly necessary.

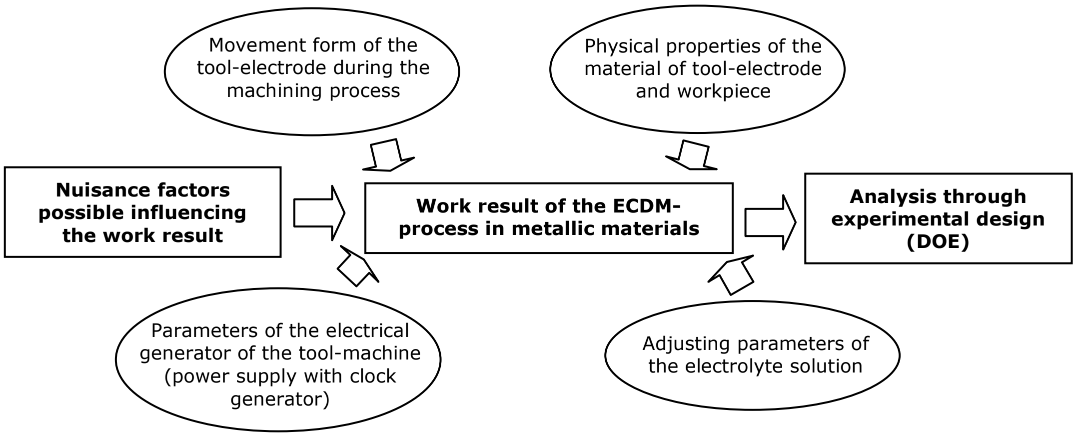

Figure 1: Parameters of the ECDM-technology influencing the work result of the machining process (input-variables to be modified in experiments)

Machining time, tool-electrode wear and diameter of machined microhole are the principal aims of the experimental analyses presented in this article. These experiments were conducted by use of a special tool-machine adequately adjusted to machine microholes with diameter smaller as 0,5 mm in steel plates applying the ECDM-technology. The experiments' results certainly serve as a broad technological base to define machining conditions to produce holes with small diameters for technical applications in injection system components of diesel and gasoline motors, aiming here to reduce production costs and improve product quality in the automotive industry in a sustainable way. In general, the hole quality (for example, diameter precision and surface roughness) is substantially influenced by the “phases” EDM (electro-discharge machining) and ECM (electrochemical machining). In other words, the work result of the ECDM-process directly depends on these process phases acting in a combined form during the machining of a microhole. In the paper's chapter “results and discussion”, the theoretical explanation for the behavior of the output-variables being experimental studied is made in terms of the phases EDM and ECM present in an ECDM voltage pulse obtained by means of the electronic characteristics of the electrical generator of the tool-machine used in the experiments. The rotation level of the tool-electrode also has a decisive influence on the development of both phases contained in this pulse and is an important input-variable to be analyzed in the experimentation of this article, still parallel to the controlled variation of other process parameters with strong effects on the ECDM-machining of the geometrical form being machined, through the application of DOE for a high performance and reliability of the experiments. The material removal of the ECDM machining procedure occurs by electric sparks (EDM-phase of the ECDM-process) taking place in the frontal working gap (frontal space between tool-electrode and workpiece in the microhole) and in the same time by electrochemical process within the lateral gap (distance of the microhole wall to the lateral surface of the tool-electrode).

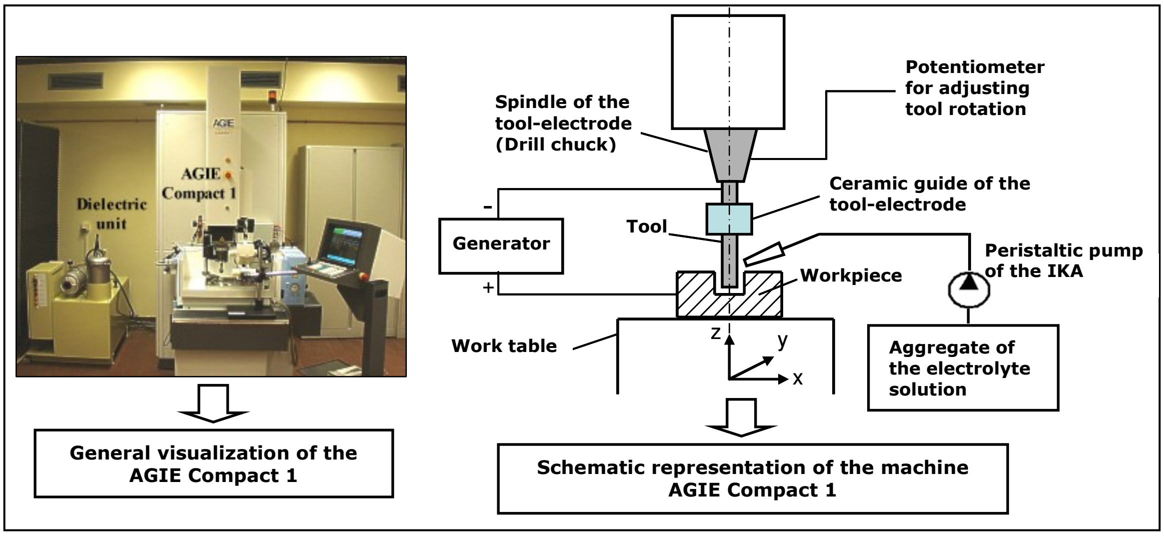

Figure 2: AGIE Compact 1 applied in the experimental investigations of the ECDM-technology

2. Experimental methodology

2.1 Technical description of the tool-machine used in the experiments

The experimentation of this work has been performed using an EDM-machine of the manufacturer AGIE Charmilles (model "AGIE Compact1") (**fig.2**).This is a special type of equipment usually applied to produce three-dimensional cavities in mechanical parts by EDM-sinking using tool-electrode rotation controlled through a potentiometer (up to 2000 RPM). During the machining process of a geometrical form (for example, a hole with small diameter), the sinking movement of the tool-electrode takes place along the Z-axis, where the rotational movement of this tool occurs around the X-axis. Here is the movement of the workpiece defined in two possible directions of the machine work table (the axes X and Y). Beyond these characteristics, the original machine concept was projected to machine parts with use of deionized water as dielectric medium of the EDM-process. The machine generator is a specific model of "relaxation generator" electronically working in the same time with a closed-loop control system, being possible in this case to adjust different parameters to perform the machining procedure: *P* (control of the total time in μsec between two voltage pulses applied to the tool and workpiece), *U* (intensity of voltage pulse in Volts), *Sbox* (precise definition of the energy of an electric spark by adjusting the capacitance in μF of a group of capacitors), *Com* (fine set-up of the distance of tool-electrode and workpiece in the frontal working gap), *Gain* (repositioning speed of the electrode in the situation of a small deviation of its positioning related to the respective condition established with *Com*). Here, the parameters *Com* and *Gain* of machine are closed-loop control variables with a strong influence on the stability of the machining in the working gap. **Fig.3** approximately indicates in the practice the operation principle of these two variables. For example, in this figure the set-up of *Com* 10 % consequently causes the adjusting of frontal working gap in 40 μm. Eventual instabilities during the machining provokes modifications of this gap dimension. In this case a repositioning movement of the tool takes place very rapidly, in function of the set-up value adjusted for *Gain*. The higher the Gain-value, the faster is the tool-electrode movement to establish once again the gap distance previously defined by *Com* 10%.

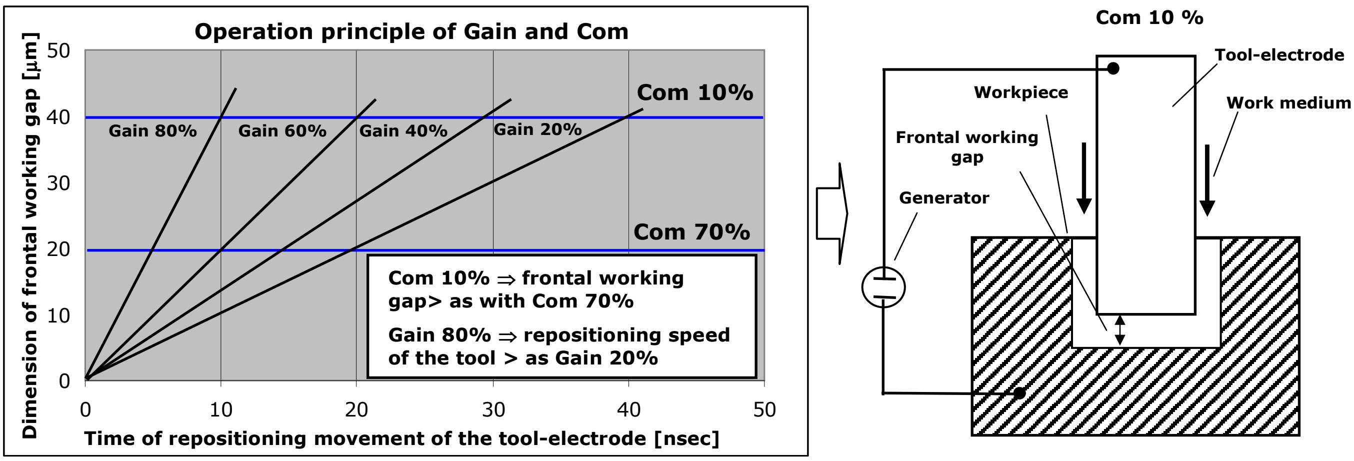

Figure 3: Interaction of Com and Gain of the closed-loop control system (AGIE Compact 1)

For the machining of microholes applying the ECDM-technology two principal modifications in the technical characteristics of the tool-machine AGIE Compact 1 were performed: 1) modifications in the programming of closed-loop control system so that the machine can tolerate a greater quantity of short-circuits during the machining process without constant repositioning movements of the tool-electrode to again establish ideal machining conditions in the working gap; 2) An alteration at the tool clamping system in the machine axis (Z), where in this case a ceramic guide of high dimensional precision was mounted between drill chuck and workpiece surface to be machined. **Fig. 4** shows a general overview of this special assembling used to produce holes with diameters smaller as 500 µm.

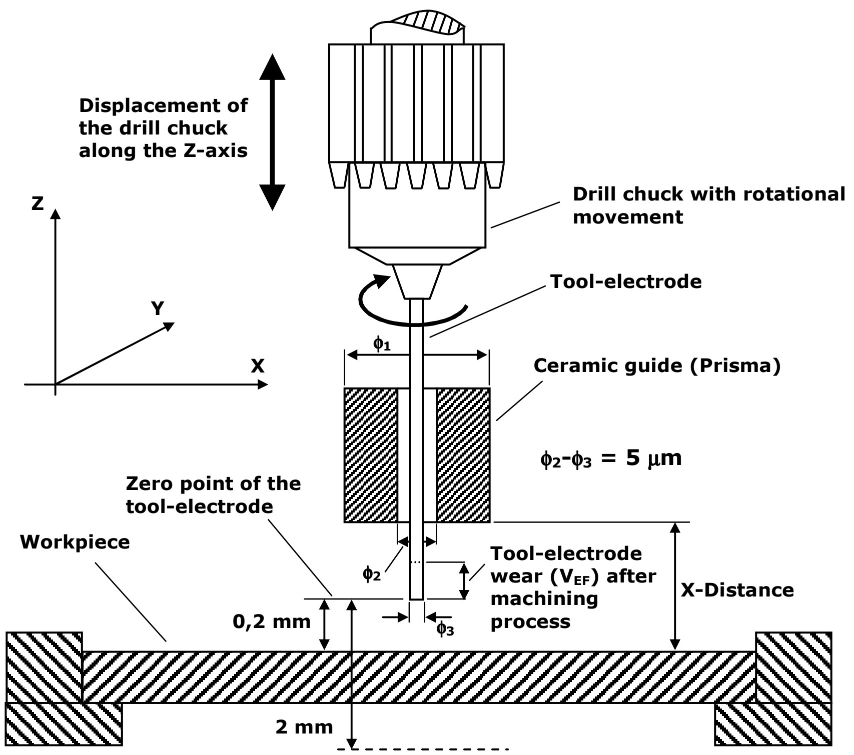

Figure 4: Assembling details of the ceramic guide of the tool-electrode in the Z-axis of the machine

2.2 Experimental planning

To perform experiments related to the machining of microholes using the ECDM-process a group of "variable and non-variable" factors was firstly defined, according to the informations described in the **table 1**. In this situation an experimental design (here a fractional factorial experiment based on the main concepts of the DOE) was developed with use of the statistical software "MINITAB", resulting in a defined number of experimental runs to be conducted. The corresponding results of these experiments (tool-electrode wear, machining time as well as internal diameter of microhole) were analyzed applying "variance analysis" (F-test) to statistically verify significant interactions between the process parameters being studied under pre-defined conditions of non-variable factors. For example, the parameter "capacitor capacitance" is an important input-variable with an expected influence on these results. The operational principle of this process parameter in the relaxation generator of the machine AGIE Compact 1 is indicated in the **figure 5**. Basically, setting up the *Sbox* in, a specific value in µF a precise control of the total energy of the EDM-phase of the ECDM-process is made consequently.

Table 1: Process parameters of the experimental analysis with the ECDM-technology

NON-VARIABLE PARAMETERS	DESCRIPTION
❒ Tool-electrode	Bar with diameter of 0,1 mm produced with tungsten
❒ Workpiece	Plate of stainless steel with thickness of 0,6 mm
❒ Electric voltage at the electrodes (u_{ECDM})	150 Volt
❒ Volume of electrolyte solution	0,9 ml/s (laterally applied at the tool-electrode)
❒ Max. machining depth	2 mm;
VARIABLE FACTORS	**DESCRIPTION**
❒ Electrolyte	Sodium chloride (NaCl) and sodium sulfate (Na_2SO_4);
❒ Electrolyte conductivity	0,1, 0,25 and 0,50 mS/cm;
❒ Rotation of the tool-electrode	100, 1000 and 2000 RPM
❒ Capacitor capacitance (Sbox)	15 nF and 25 nF

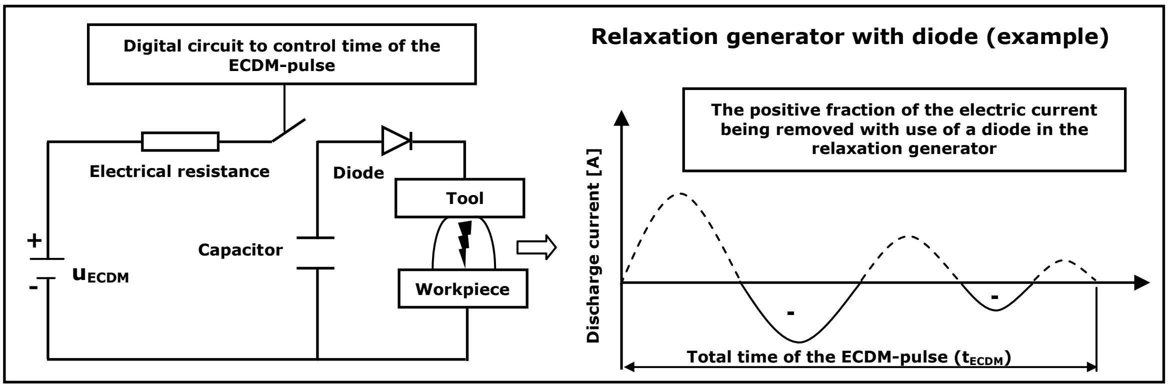

Figure 5: Basic operating principle of the parameter Sbox in the generator of the AGIE Compact 1

3. Results and discussions

3.1 Analysis of the machining time

The experimental results related to the machining time presented in the **figure 6** correspond to a machining depth of 2 mm. The tool-electrode, whose displacement movement in the Z-axis is controlled through the closed-loop control system of the AGIE Compact 1, penetrates until this maximum depth (see **figure 4**) with a rotational velocity, that is, this condition is valid for all groups of experiments presented in the graphics of this following figure indicating statistically significant interactions between process parameters of the ECDM-machining. These interactions were precisely determined through a F-test performed with the MINITAB, using here a significance level of 5 %.

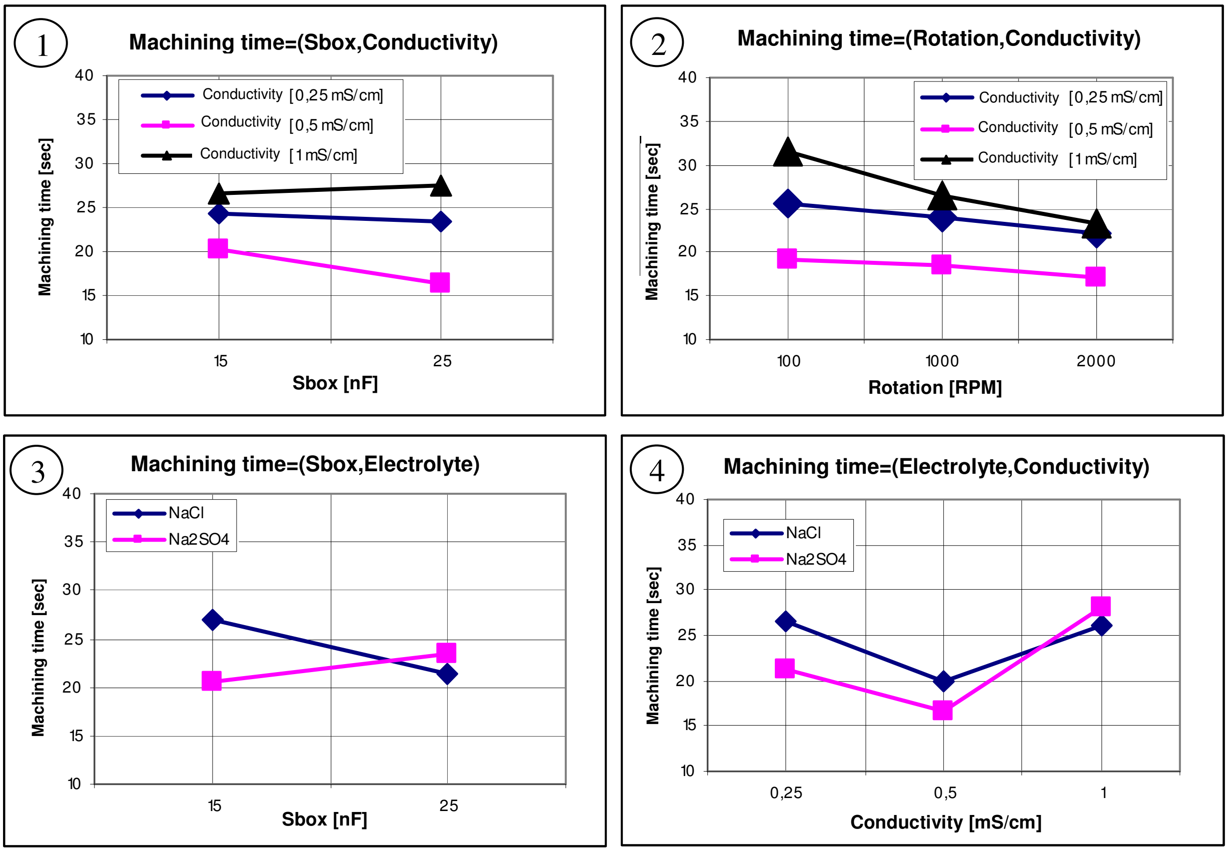

Figure 6: Result related to the machining time of the ECDM-process

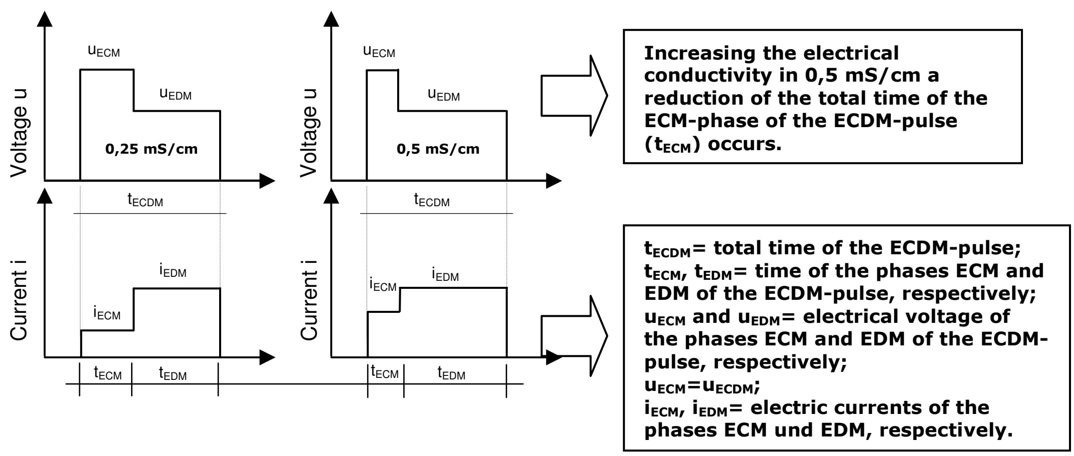

Figure 7: Influence of the electrical conductivity on the characteristics of the ECDM-Pulse

In the graphic 1 of the **figure 6**, an interaction between *Sbox* and electrical conductivity of the electrolyte solution can be visualized. A small increase of conductivity up to 0,5 mS/cm (independently of the chemical composition of the electrolyte solution) causes a significant reduction of the machining time to produce a microhole with the ECDM-technology. This increment in mS/cm has as direct effect the strong minimization of time of the ECM-phase of the ECDM-pulse, what consequently provokes the enlargement of the energy of the EDM-phase of this pulse. For a better understanding of this affirmation, the **figure 7** is presented, where in this case a hypothetical ECDM-pulse is indicated. Here can also be seen the addition of electric current (i_{ECM}) provoked with the conductivity increase. Experimental results show that a strong correlation between the parameters i_{ECM} and t_{ECM} exist, that is, a gain of time by a modification of electrolyte conductivity is directly conditioned to a reduction of i_{ECM}, and vice-versa. But this condition is not valid applying conductivity values beyond 0,5 mS/cm. High values related to this process parameter (1 mS/cm) conduces to constant short-circuits during the hole machining process, what constantly provokes interventions of the closed-loop control system of the tool-machine to minimize these problems. Furthermore, as identified in the graphic 1, the use of a higher value of *Sbox* causes a minimization of the time necessary to machine a microhole with ECDM-process, for 0,25 mS/cm and 0,5 mS/cm. The use of a capacitor capacitance in 25 nF makes it possible to increase the available energy of an electric discharge during the EDM-phase of the ECDM-Pulse, where with good washing condition of the debris from the working gap (through a correct hydraulic flow of the electrolyte solution) a rapid penetration movement of the tool-electrode in the workpiece being machined is thus achieved, reducing consequently the ECDM machining time. The debris volume with *Sbox* in 25 nF significantly enhances compared with 15 nF, because that per ECDM-pulse a greater quantity of material is removed from the tool-electrode and workpiece in form of very small particles with spherical geometry and high hardness. However it is expected in the practice that a considerable enhance of the machining time takes place with use of *Sbox* greater as 25 nF, due to the fact that an immense volume of removal particles is produced in the lateral and lateral working gap. Only with a readjustment of the electrolyte flow or closed-loop control system of tool-machine is probably possible to establish again optimized machining conditions to achieve the desired machining time. Beyond the influence on the time of machining process, an alteration of capacitor capacitance in high values tends to increase the dimension of “discharge crater" in the surface of the electrodes. This is direct cause of quality reduction immediately in the hole surface (greater roughness and thermal stresses in the workpiece surface). An improvement of the surface quality in an acceptable condition can be done increasing the electrolyte conductivity, but this once again has consequences on the total time of the ECDM machining procedure as consequence of enormous modifications in the output parameters of the ECDM-pulse (i_{ECM}, t_{ECM} and i_{EDM}). In other words, alterations of *Sbox* and conductivity of the electrolytic medium must be made interactively, so that the best work result of machining process can be reached in producing microholes in stainless steel.

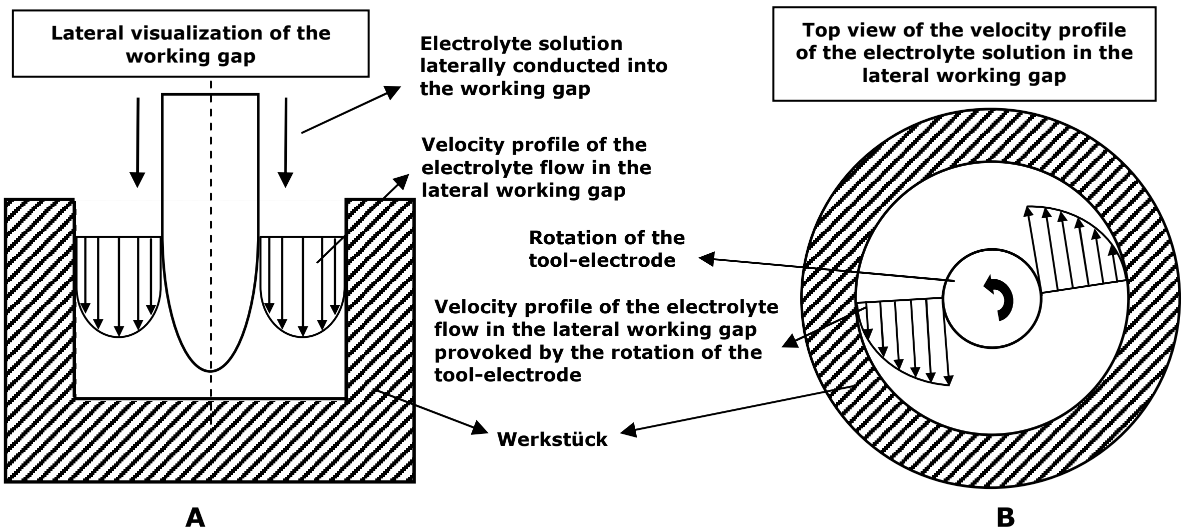

Figure 8: Velocity profile of the electrolyte flow in the working gap provoked by the rotation of the tool-electrode

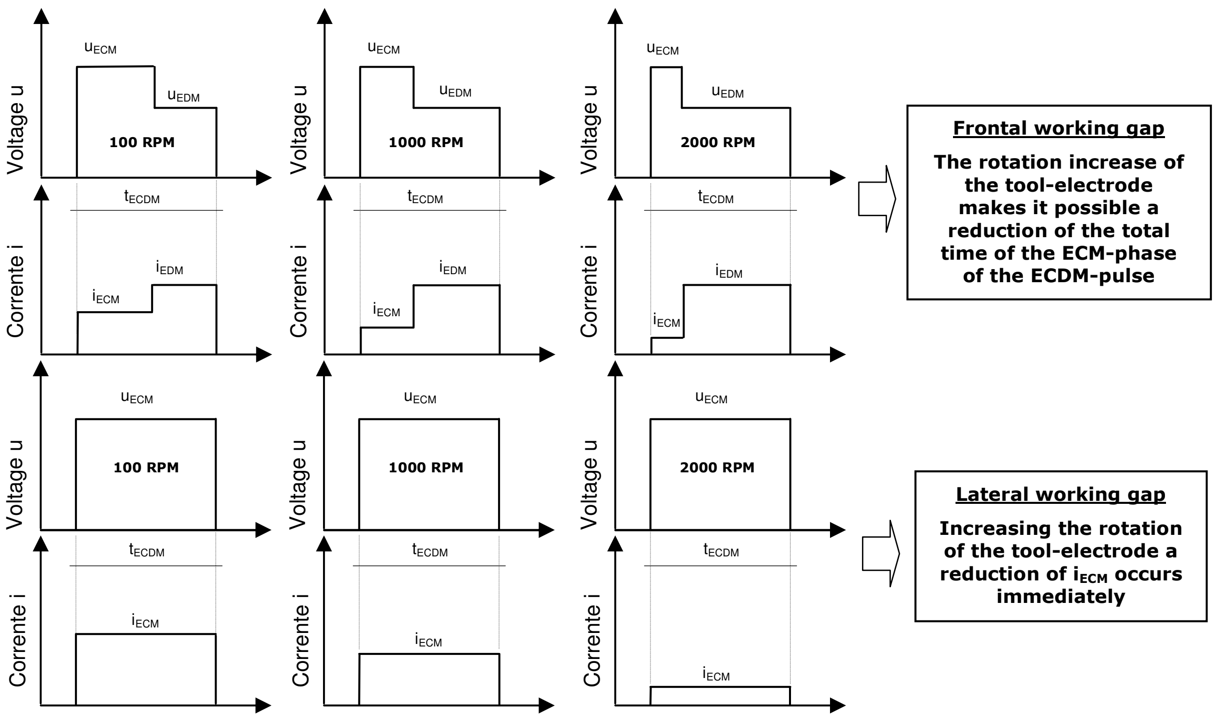

Figure 9: Influence of the tool-electrode rotation on the output variable of the ECDM-pulse

The graphic 2 of the **figure 6** shows that greater values relating to the rotation of the tool-electrode conduces to a reduction of the ECDM-machining time, independently of the respective adjustment of the electrolyte conductivity. With this rotation a special velocity profile of electrolyte flow is developed in the lateral working gap (see **figure 8**), where consequently a rapid removal of debris from the machining area is here obtained, thus conducing to positive effects to the machining time. Furthermore, a second important influence of the tool-electrode rotation is explained through the **figure 9**. The rotation increase makes it possible the generation of a significant volume of gases (water vapor) within the space between tool-electrode and workpiece, through a temperature increase produced by mechanical friction in the electrolyte solution. These gases quickly fill the working gap, what consequently causes a reduction of the time (t_{ECM}) and electric current (i_{ECM}) of the ECM-phase of the ECDM-Pulse. In this small gap there is now a mixture of water vapors (provoked by the rotation of the tool-electrode) and hydrogen (resulting of electrochemical reactions during t_{ECM}). At the exact moment that this thermodynamically complex mixture electrically isolates the gap between electrodes, the start of the EDM-phase (with defined i_{EDM} and t_{EDM}) takes place rapidly (initiation of an electric discharge due to the development of a plasma channel throughout a gas). Moreover, the **figure 4** indicates ECDM-pulses without the presence of the phase related to the electrical discharge machining of the ECDM-process. Some specific forms of pulses normally appear in the lateral working gap during the machining process, when the distance of tool and workpiece is too large. Here, the raise of the tool-electrode rotation has only an effect on the minimization of the intensity of current i_{ECM} by the elevated gas generation in the gap. Certainly a constant increase of the tool-electrode rotation would cause a total elimination of i_{ECM}, what is absolutely not desirable in the practice. The presence of a minimum fraction of this electric current within the ECDM-pulse is extremely important to ensure the surface smoothing of the microhole being machined with ECDM-Technology. The EDM-phase of this pulse provokes small discharge craters on the microhole's surface, whereas the ECM-phase (due to i_{ECM} occurring in defined time) must conduct to a perfect flattening of these craters [1] for achieving the best roughness. Each crater can be characterized in the practice by a diameter and depth as consequence of the parameters i_{EDM} and t_{EDM}. The interaction between crater geometry, electrochemical phase of the ECDM-process and chemical composition of the electrolyte solution defines here the final roughness of the machined microhole. The utilization of the electrolyte Na_2SO_4 enables, at the hole's surface, the generation of oxides (passive layer) composed with chemical elements of the workpiece material. Using NaCl the possibility of formation of this layer does not exist, what is responsible for a bad surface quality of the microhole. This important difference related to these electrolyte solutions explains other experimental results that will be presented in the sequence of this paper. The electrochemical characteristics of the negative ions of the Na_2SO_4 and NaCl when dissociated in water have a considerable influence on the material removal of the ECDM-machining. Because the raise of the tool-electrode rotation conduces to a strong increase of the electrolyte temperature, a special effect on the electrochemical mobility of the ions of the electrolyte indicated above is then expected. This situation causes a modification of electrolyte conductivity, provoking alterations on the output parameters of the ECM-phase of the ECDM-pulse, so conducting to direct consequences on the machining time. Furthermore, the rotation rise of the tool-electrode tendentiously creates in the working gap the appearance of severe turbulent conditions relating to the electrolyte flow, where in this case a heat flux to the microhole's surface predominantly appears in the convective form. The oxide layer formed on this surface (with passivating electrolyte) the first barrier to the convective heat transfer from the working gap to deeper regions of hole wall, which are approximately at temperatures of 25 °C.

In the graphic 3 of the **figure 6** it can be visualized that the use of *Sbox* in 15 nF with Na_2SO_4 produces a shorter machining time. Using this adjustment condition to machine a microhole with the ECDM-process, a reduction of electrical short circuits between tool-electrode and workpiece is obtained during the machining procedure. With the electrolyte NaCl (non-passivating medium) the development of a passive layer on the hole's surface does not occur. In other words, the working gap is likely to generate short circuits during the machining process, what constantly conduces to repositioning movements of the tool-electrode in the Z-axis of the tool-machine trying to establish adequate work conditions in the gap. Certainly the application of *Sbox* in 25nF provides a substantial increment of the energy of the EDM-phase of the ECDM-pulse, thus causing an undesirable presence of large volume of debris in the ECDM-machining. For the sodium chloride this high energy causes a minimization of the ECDM-machining time due to a greater material removal of the workpiece. In the case of sodium sulfate, this energy hinders the complete formation of an oxide layer on the hole's wall. Here, there is the growth of a passivating layer with several porosities which allow a direct contact of the electrolyte solution with the workpiece material having elevated electrical conductivity. The explanation for the appearance of these porosities is that during the total period of the EDM-phase (with capacitor capacitance in 25 nF) a stronger oscillation of the discharge current in positive and negative values (comparatively to 15 nF) takes places between the electrodes. This current oscillation is a consequence that the power supply of the machine AGIE Compact 1 is type of relaxation generator. Furthermore, it is expected in the practice that an excessive increment of *Sbox* beyond 25 nF probably provokes a rise of the ECDM-machining time for both electrolyte solutions, mainly due to the fact that an enormous quantity of removal products of the material being machined is produced in the working gap. These products have a high tendency to the formation of particle chains at the electrodes' surface, consequently producing short circuits which are responsible for a negative effect on the machining time due to extreme instabilities in the ECDM-machining process. Fundamentally, a direct consequence of the higher process time with NaCl (comparatively to Na_2SO_4) is a large rounding radius that appears immediately at the inlet side of the tool-electrode (external diameter) in the microhole during machining process. So, the non-passivating characteristics of the NaCl has an immense influence on the total dimension of this radius, because of the non-formation of a passivating layer on this hole area. Eventually in the case of using different chemical compositions of passivating electrolytes, a specific influence on the radius dimension at the external hole diameter is expected. Each one of these electrolyte solution produces a passive layer with characteristic property of electrical resistance. This total resistance acts a barrier against the electrochemical current produced during the ECDM-machining at the external diameter, thus controlling its final geometry. For example, the presence of Al in the material of the workpiece can conduce to the development of passive layers as base of Al_2O_3, consequently causing a considerable diminishing of i_{ECM}, due to a high electrical isolation provoked by this compound within the working gap.

The graphic 4 of the **figure 6** indicates significant differences between the process parameters being studied, related to the output-variable "machining time". Firstly, the difference encountered here relating to the NaCl and Na_2SO_4 certainly confirms the experimental results presented in the graphic 3. For both electrolyte types, a conductivity increase up to 0,5 mS/cm causes a strong reduction of the ECDM machining time. This is a clear confirmation of the result shown in the graphic 1 relative to the electrical conductivity, where here the increment of this process parameter leads to a minimization of the total time of the ECM-phase related to the ECDM-pulse and, in the same time, an expansion of the electrochemical current i_{ECM}. Fundamentally, an alteration of electrolyte (from sodium sulfate to NaCl) practically has the same consequence as a modification of electrical conductivity of 0,25 mS/cm to 0,5 mS/cm, since in both cases of parameter modifications of the ECDM-process a decrease of t_{ECM} (together with an increment of i_{ECM}) takes place normally. For example, the non-presence of a passive layer in the working gap during the machining process with sodium chloride is responsible for the accentuated development of the current i_{ECM} because the low electrical resistance created in the space between tool-electrode and microhole being machined. The high current produces a greater volume of removal particles in the working gap which tend to generate short circuits, thereby impairing the ECDM-machining time due to the constant movement interruptions of the Z-axis, even the closed-loop control system of the tool-machine constantly working to avoid this. Moreover, independently of the influence of NaCl and Na_2SO_4 indicated above, both electrolytic solutions have the task in the ECDM process to produce hydrogen gas at the surface of the tool-electrode (in according to **eq.1** and **eq.2**), consequently enabling the generation of electric sparks which are responsible for material removal of the workpiece during machining. The formation velocity of this gas between the electrodes controls the total time relative to the ECM-phase, and so the time of the EDM-phase of the ECDM-pulse, controlling in this way the characteristics of the ECDM-machining, that is, predominantly through mechanisms of the electrical discharge machining or electrochemical machining. Finally, it must be indicated here that the gas O_2 developed in the **eq.2** chemically reacts with the atoms of the workpiece material, creating in this case a passive layer on the workpiece surface with considerable electrical resistance, but reducing roughness surface according to the corresponding pair "workpiece material/electrolyte solution". In practice, outside the scope of the experimental investigations of this work, there are diverse possibilities to combine this pair (mainly using here non-passivating electrolytes) so that specific experiments can be conducted using the ECDM-technology for machining holes with small diameters, and consequently to exactly investigate the formation process of passive layers with special morphology and electrical properties. These layers have so a direct influence on the work result of the ECDM-machining, principally on the material removal rate and superficial quality of the microhole being machined.

$$2H_2O + 2NaCl \rightarrow H_2(g) + Cl_2(g) + 2Na^+ + 2OH^- \quad \textbf{(1)}$$

$$2H_2O + Na_2SO_4 \rightarrow 2H_2(g) + O_2(g) + 2Na^+ + SO_4^{-2} \quad \textbf{(2)}$$

3.2 Analysis of tool-electrode wear

The measurement of the tool-electrode wear (frontal wear, respectively V_{EF}) was made according to the following procedure: After the machining process of a microhole, the tool-electrode presents a wear (see also **figure 10**), in dependence on the respective adjustment of ECDM-parameters to perform this machining, and is repositioned again at the zero point of the Z-axis of the tool-machine. To exactly measure V_{EF}, the electrode is firstly moved to other position of the plane XY (by manual mode of open-loop controller of the machine) and then displaced until the appearance of a contact with the workpiece surface. The mathematical difference between the distance traveled by the tool to this contact point and the value of 0,2 mm is defined as the total electrode wear.

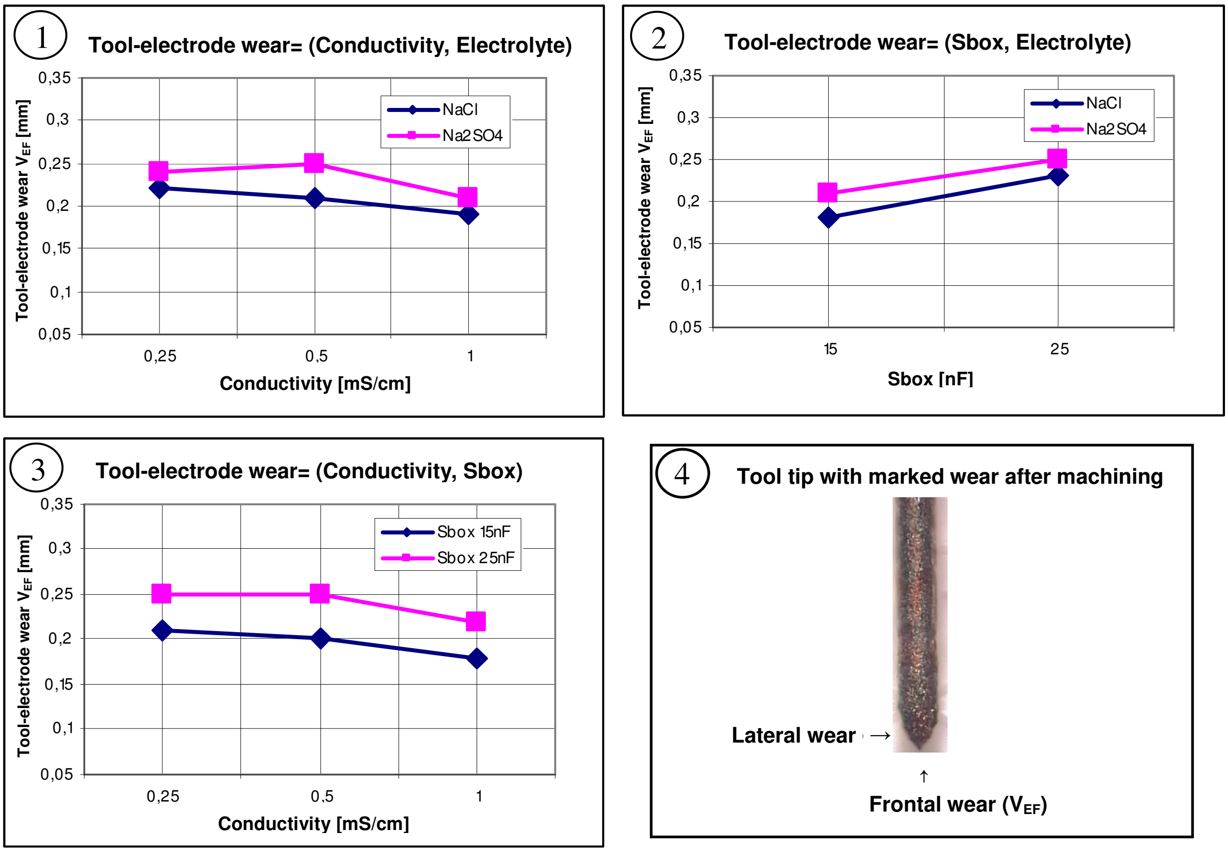

Figure 10: Influence of the modification of ECDM-parameters on the tool-electrode wear

Fig.10 presents in details the experimental results relating to the modification effect of ECDM process parameters on the tool-electrode wear (frontal wear, respectively V_{EF}). Here is indicated in the graphic 1 that this wear is more defined using Na_2SO_4 as work medium of the ECDM-process, although the machining time with this electrolyte solution is less than NaCl normally applying *Sbox* in 15 nF and electrical conductivities between 0,25 and 0,5 mS/cm. The formation of a passive layer on the hole surface during machining, with the passivating electrolyte, tends to generate electrical sparks within the lateral gap (besides discharges taking place in the frontal gap), what consequently increases the total wear of the tool-electrode tip. The graphic 2 of the **figure 10**

also demonstrates the direct consequence of the both electrolytes on the output-variable of the ECDM-machining being studied. In this graphic (and in the graphic 3), the effect of the variation related to Sbox on the electrode wear is verified as well. Larger values of this input-variable provoke the energy rise of the EDM-phase of the ECDM-pulse, causing a wear increase of the tool-electrode due to the high volume of its material being melted during an electrical discharge. Finally, it can visualized in the graphics 1 and 2 that an alteration of conductivity of 0,25 to 0,5 mS/cm tendentiously causes a reduction of the tool-electrode wear. This conductivity increase generates a minimization and an increment of the time and current of the ECM-phase of the ECDM-process (increasing here the energetic content available for electrochemical removal), respectively. In this case there is an expansion of the total period of the EDM-phase, directly provoking an energy growth of this phase. The energy increment of both process phases is responsible for conducting the hole's machining more rapidly, consequently requiring a smaller quantity of ECDM-pulses to machine the entire hole, reducing so the tool-electrode wear, laterally and frontally. However, it is normally expected that an excessive increment of electrolyte conductivity will conduct to a significant increase of the total time related to the phase of electrical discharge machining of the ECDM-pulse, consequently producing an undesired growth of electrode wear. The optimal adjustment of this input-variable of the EDM-machining to enable the best result relating to the wear value can be only made by means of extensive experimental investigation, verifying in the same time what types of direct effects will be produced on the other output-variables of the machining process, certainly including here the machining time which is strongly influenced by the high presence of removal products in the working gap in random form. Since the electrical conductivity has a considerable effect on the volume of debris of the ECDM-process, small corrections of the volumetric quantity of electrolytic solution to machine a hole can normally conduct to a minimization of short circuits between electrodes, probably enhancing the overall performance of the hole's machining, with reduction of the machining time and definition of better conditions relating to the frontal and lateral wear of the tool-electrode (graphic 4 of **fig.10**). The intensity of lateral wear of the tool tip has a high influence on the dimensional precision of the machined microhole. To correctly minimize the negative effect of this wear on the hole geometry, it is normally necessary to penetrate the tool-electrode in the workpiece being machined deeper as the hole thickness (in this case 0,6 mm). This condition is ensured by using a machining depth of 2 mm in the experimental investigations of this work, as indicated in the **fig.4**. Increases in the penetration depth of the electrode consequently lead to small increments in the machining time. Reaching the maximum penetration depth, the relaxation generator the tool-machine is automatically turned off and the electrode rapidly moves to the zero point of the Z-axis, what prevents any form of material removal (electrochemically or through electric sparks) on the hole's surface. Surely in specific applications of the ECDM-technology to produce microholes, by special programming of the pulse generator of the tool-machine, only an electrochemical material removal during the return movement of the tool-electrode can be advantageous to reduce roughness peaks on the hole surface.

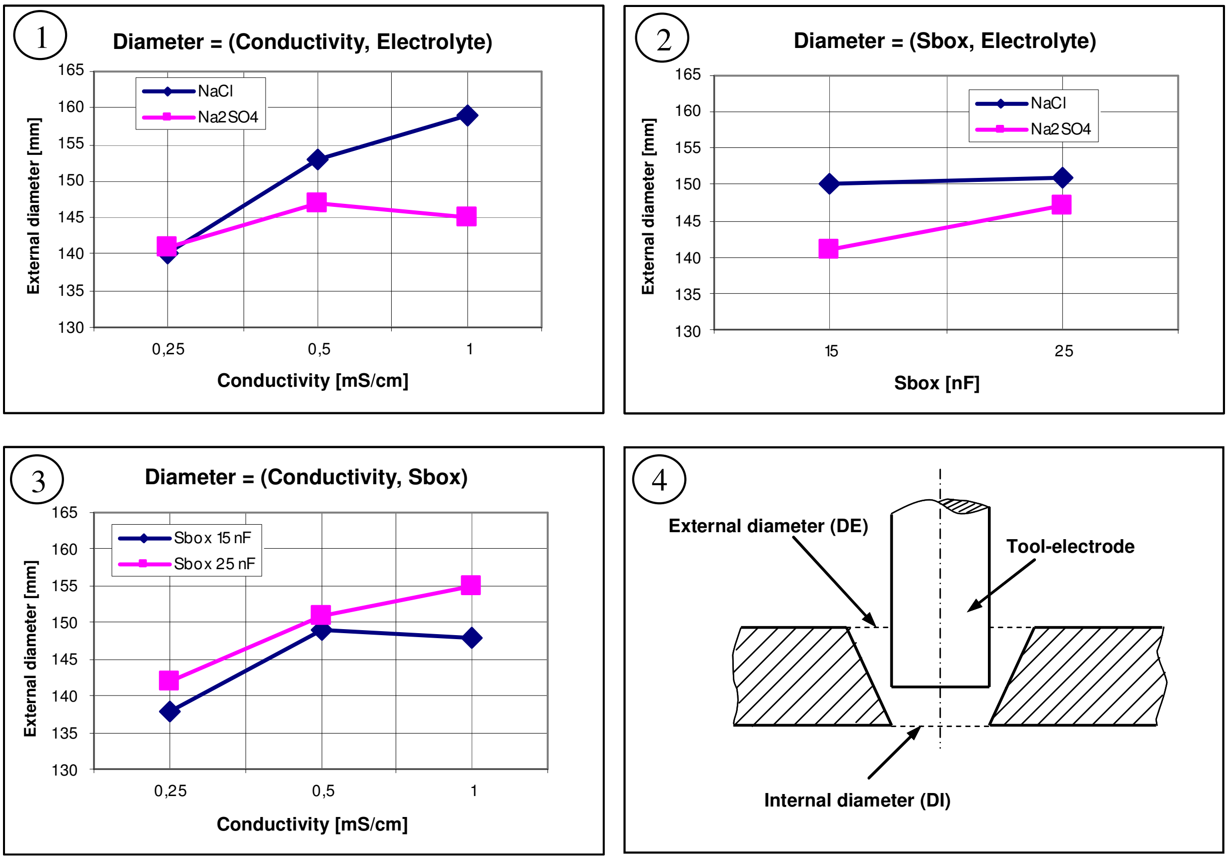

Figure 11: Influence of ECDM-parameters on the external diameter of the microhole

3.3 Analysis for diameter of the machined hole

Fig.11 indicates the influence related to the modification of ECDM-parameters on the external diameter (see graphic 4) of the machined microholes. As verified in the graphics 1 and 3, the increase of electric conductivity leads to larger diameters of the holes produced with the ECDM-technology. A more expressive intensity of conductivity extensively enhances the energetic content of the electrochemical phase of the ECDM-pulse, causing a high material removal (through the ECM-phase) on the hole's wall and so increasing the hole diameter. Since during the ECDM-machining process the electrolyte solution is constantly in contact with the external diameter (DE) of the microhole being machined, there is here a continuous material removal. At the internal hole diameter (DI) a material removal takes place practically from the time immediately after the “hole rupture”. Because the machining procedure quickly stops after this rupture, it is thus expected in this case that the final dimension of the DE is greater DI, what conduces to the direct development a hole conicity. This conicity reaches values of approximately 20 up to 30 µm, dependently on the setup of other parameters of the ECDM-process. The conicity intensity of the hole can be very important in specific applications of the machined workpiece in special industrial fields, as for example, in the field related to the injection systems for the automobile industry, where the geometrical shape of the hole has a decisive task in reducing the emission grade of the vehicle motor.

Through the informations of the graphics 2 and 3 it can be stated that the increase of *Sbox* leads to a considerable increment of the external diameter of the microhole. The capacitor capacity adjusted in 25 nF expands the total energy of the EDM-phase of the ECDM-pulse, what enables a more strong material removal by the mechanisms of electrical discharge machining of the ECDM-process. However, it is expected in the practice that increments in this process parameter beyond 25 nF cause a high generation of machining debris within the working gap as well as a pronounced wear of the tool-electrode, thus minimizing the total performance of the ECDM-machining process outside acceptable limits. To correctly compensate this problem, either a decrease of the ECDM-pulses (increasing the pause time between these pulses) or the use of greater volumes of electrolyte solution in the electrodes' gap are necessary to further improve the process efficiency in a desired technical condition. Excessive settings of pause times is responsible for high machining times, that is, a condition totally undesired for this application of the ECDM-technology due to the low material removal rate, mainly thinking in the possibility to use this machining process in production line of a industry with reduced product cycle time, aiming to minimize product costs to gain a better market position. Moreover, according to the practical experience, the use of high values related to the capacitor capacity also has as direct effect the generation of hole surface with elevated roughness and thermal affected zone (TAZ). Both surface characteristics have a very important contribution to the fatigue resistance of the mechanical component produced with the ECDM-process, what in some situations defines the reliability grade of this part under the influence of strong mechanical loads. One of the objectives of the ECDM-machining is just to improve the superficial properties of the machined part. Normally, the total electrical power of the ECM-phase of the ECDM-pulse available for material removal should be correctly set up (for example, by the adjustment of the electrical conductivity of the electrolyte solution) so that surface irregularities (also including here micro-porosities and micro-cracks) caused by excessive adjustment of *Sbox* can be compensated perfectly. The complete elimination of superficial irregularities produced by means of high intensity of the condenser capacity defines more or less corrosive and cavitation resistance [2] as well as tribological properties of the machined microhole. This corrosion resistance certainly depends on the physical characteristics of the passivating layer formed on the hole surface as direct consequence of the chemical composition of the electrolyte solution used to perform the ECDM-machining process. The passivating layer thickness consequently determines a level of electrical resistance in the lateral working gap, thus defining the intensity of electrochemical current of the ECM-phase of the ECDM-pulse. Different techniques of surface analyses (for example here, X-ray diffraction) can be correctly applied to identify the properties of this layer in according to the respective combination of process parameters *Sbox*/electrolyte solution that thus leads to a special material structure of the passivation layer formed on the hole surface. As consequence of the peculiar characteristics of the ECDM-machining, it is expected that this layer presents different thicknesses and physical properties along the machined hole.

The experimental results presented in **Fig.11** related to the electrolyte solution applied to machine microholes indicate that NaCl makes it possible to produce larger external diameters than Na_2SO_4. These results are certainly explained due to the non-passivating characteristics of the sodium chloride which do not enable to develop a passive layer on the hole's surface during the ECDM-machining process. Other striking feature of NaCl is that this working medium generates a hole surface with high roughness, totally non-adequate as work result of the ECDM-machining, what excludes the use of non-passivating solutions from the applications of the ECDM-process in steels. Furthermore, beyond the technical aspect related to the possibility of formation or non-formation of passive layers on the microhole being machined and so an influence on the hole geometry, important differences between the working media can be found in the electrochemical mobility of their negative and position ions which define the intensity of electric current and total time of the ECM-phase of the ECDM-pulse. Ions with a high mobility (in dependence on an activity coefficient) consequently lead to a rapid development of the electrochemical phase of this pulse. In this special case, there is a broad range of possibilities to combine chemical compositions of electrochemical solutions to achieve the optimized result relating to hole surface and geometrical form of the hole as well as material removal rate and tool-electrode wear. The choice of the electrolyte solution should be also made so that the generation of hydrogen gas at the tool-electrode surface can be ensured to promote the correct formation of the EDM-phase of the ECDM-process to efficiently conduct the material removal of the part being machined. Here, the direct use of a combination of electrolytes that easily generates gas vapors through heating (during the ECM-phase) is also a important condition to make it possible to product electrical sparks between electrodes, to facilitate the phase of electrical discharge machining of the ECDM-technology in the correct time period after the electrochemical phase. The energetic content of the plasma channel of this process phase could also be increased with the mixture of an organic substance in the combination of electrolytic solutions. During the electrical discharge, this substance can act as a barrier to the plasma channel expansion, thus increasing the total energy of this discharge available for material removal. Furthermore, the electrolytes applied in the ECDM-machining can be combined aiming the minimization of chemically precipitated products from the electrochemical phase correspondently to the ECDM-pulse, so that with this, a reduction of short circuits can be achieved during the machining process of a microhole, what makes it possible to obtain advantages in the machining time and consequently in the material removal rate. The value of electrical conductivity of these precipitates defines the probability grade to generate electrically conductive chains particles between tool-electrode and workpiece and thus to produce a short circuit, either in the lateral or frontal machining gap. In the practice, a technical verification of electrical short circuits produced with use of a specific electrolyte solution can be conducted by the application of a special measurement technique to the ECDM-machining, for example analyzing the output variables of the ECDM-pulses.

4. Conclusions

The experimental analysis of machining time, tool-electrode wear and geometry of microholes indicates that the work result of the ECDM-machining is strongly influenced by the input parameters, where in this case new perspectives for the future realization of other experiments related to electrolyte solutions and electrical parameters of the machine generator were introduced. Additional studies for the superficial quality of machined microholes with the ECDM-technology can be also defined here as an important point of these experiments used specific part materials to be machined. The utilization of different materials enables to get profound informations about the physical characteristics of passive layer on the hole surface using passivating electrolytes. These properties, in dependence on the part material being machined, creates an electrical resistance within the lateral working gap that precisely controls the total energy of the ECDM-process available for material removal. This certainly justifies research works referring to the special applications of the electro-chemical discharge machining to produce mechanical parts with high dimensional precision and excellent surface quality. Furthermore, because the technical data obtained mainly with the experiments of tool-electrode wear, new possibilities are opened up to develop electrode materials for performing machining processes of high performance and low costs by a reduction of electrode wear. These materials should be capable to facilitate the flow of electrical current during the ECM-phase and in same time to resist to the high temperatures generate by the plasma channel formed in the EDM-phase of the ECDM-pulse. In these applications, modern data acquisition systems [3] electrically coupled at the EDM-machine are an extremely effective tool for analyzing the output variables of the ECDM-pulses (current and voltage) under the use of different materials of tool-electrode being studied in experiments.

A point to be mentioned is that the experiments results also stimulate the development of new ECDM-machines, especially machines equipped with specific generators to improve material removal rate and surface quality of machined hole as well as to reduce tool-electrode wear. A high technical efficiency of an ECDM-generator surely depends on its electrical coupling with a closed-loop control system projected to rapidly detect anomalies in the working gap during the machining process of a microhole. The electrical characteristics of this generator for the fine adjustment of the electric energy of the ECDM-pulse, combined with a high quality of mechanical construction of ECDM tool-machine, determine the geometrical precision of the produced holes.

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