DETERMINING THE INFLUENCE RELATED TO DIELECTRIC FLOW OF THE EDM-PROCESS ON THE GEOMETRY OF MICRO HOLES FOR INJECTION NOZZLES

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Abstract:

The paper's objective is an experimental investigation to verify the variation effect of dielectric quantity of the electrical discharge machining on the geometrical characteristics of micro holes machined in injection nozzles fabricated with steel 18CrNi8 and with the technical denomination of DSLA. These experiments consist in the controlled modification of internal volumetric flow of the dielectric of the EDM-process (deionized water) using the DOE-methodology "One-way ANOVA", analyzing in the sequence as work result of the machining process the diameter of the micrometric holes (approximately with diameters of 0,12 mm) produced by use of tungsten bar with total diameter of 0,085 mm as tool-electrode. Such machining procedure was performed in an EDM-machine specially constructed to machine holes in injection nozzles of diesel injection systems, model AGIE Quadraton. The experiments' results clearly indicate that the increase of the dielectric volume is responsible for a considerable reduction of internal diameter of the injection holes fabricated in an injection nozzle. This reduction provokes significant consequences on the conicity of the micro holes, consequently having a very high importance for the fuel injection process in the combustion chamber of a diesel motor equipped with a specific quantity of injection nozzles.

Keywords: injection nozzles, electrical discharge machining, micro holes, 18CrNi8, dielectric, diesel motor

1. INTRODUCTION

Today the electrical discharge machining (EDM) has definitely gained an established position within the non-conventional manufacturing techniques in mechanical engineering as the main technology to machine micro holes in injection nozzles for special applications of diesel motors. Using this machining process it is possible to produce holes with elevated productivity in the production lines of the automobile industry (suppliers of injection nozzles) and with high geometrical characteristics for their respective motor applications. The geometry and surface quality of the injection holes of such nozzles have the technical function of an extremely precise control of the fuel injection process in the motor chamber. These holes' characteristics can be obtained only using the EDM-technology with appropriate conditions relative to the tool-machine, process parameters and tool-electrode, also being this machining characterized by reduced process cycle time, optimized material removal rate as well as minimal tool-electrode wear. Furthermore, the process capability index of the EDM-machining (*cp* and *cpk*) applied to fabricate injection nozzles in great quantities is certainly in according to the desired specifications of quality management system (QMS) of an industry aiming to achieve the maximal reduction of costs referring to produced products. Generally the technological application of the electrical discharge machining for these types of nozzles is encountered in the fabrication of micro holes with diameters between 90 until 500 µm. Other alternative technologies of non-traditional machining processes, as for example here, ECM-machining, ECDM-process (electrochemical discharge machining process), femtosecond laser pulse or electro-beam technology, actually have some disadvantages against the EDM to produce micrometric holes in large manufacturing scale. An important advantage of the EDM-machining process compared with the above mentioned technologies is the possibility to machine diverse holes in sequence with diameter measure ranging in ± 5 µm.

The EDM-machining of injection holes presents a great number of process parameters to be adjusted. Normally there is an immediate need for performing statistically controlled experiments to determine the best machining conditions of a micro hole. Parameters related

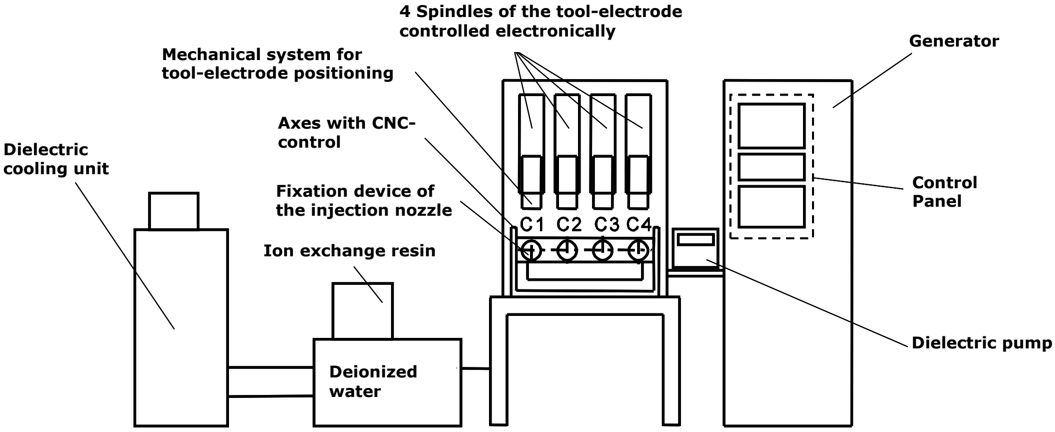

Fig. 1: EDM-machine AGIE Quadraton I of the company AGIE Charmilles

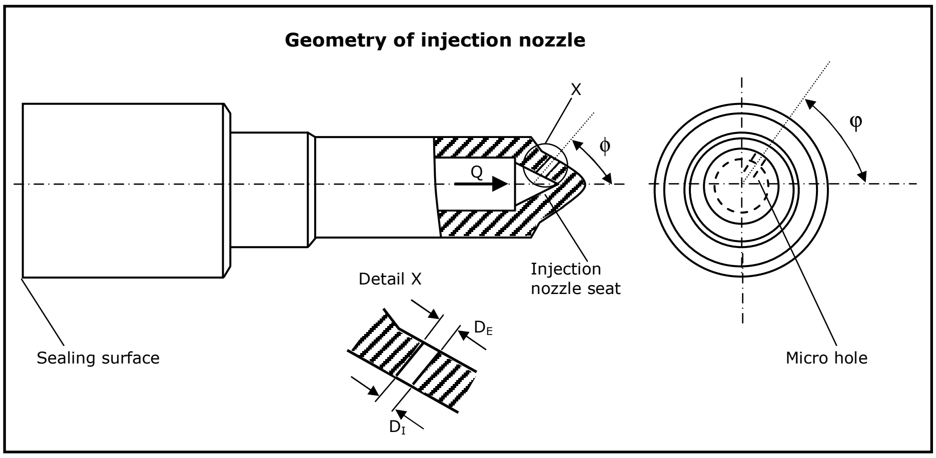

Fig. 2: Injection nozzle "DSLA" constructed with steel 18CrNi8

to the mechanical adjusting of the tool-machine, generator, tool-electrode and dielectric are defined in specific levels to achieve the exact result of the EDM-process. For example, electrical conductivity and flow of the dielectric medium into the working gap have here a task in controlling the machining precision of the hole being machined. Through an experimentally structured study, based on the fundaments of DOE, this article gives a special attention to the influence relating to the adjustment of the dielectric flow on the geometrical characteristics of injection holes produced with the electrical discharge machining. In this situation, variations of dielectric volume in g/sec are made to investigate their resulting effects on the final dimension of the "internal diameter" of these machined holes. Before the presentation and discussions of the correspondent experiment results the paper content deals with a detailed description of the equipments used to conduct experiments, giving a focus on the different forms of dielectric flows (internal and external) commonly applied in the practice to fabricate micro holes in injection nozzles by electrical discharge machining. A profound comprehension of these flow forms is very important for the subsequent interpretation of the experiments' result.

2. EXPERIMENTAL METHODOLOGY

The experiments were conducted with use of an EDM-machine model AGIE Quadraton I (**figure 1**) produced by the company AGIE Charmilles. The principal units of this equipment consist of mechanical systems for precise fixation of the tool-electrode and workpiece (injection nozzle) in their axes, aggregate for dielectric preparation (container of the ion exchange resin and dielectric cooling unit), dielectric pump (model PA-SF, IKA), generator electronically coupled with a control system for monitoring and optimizing the EDM-machining process. Moreover, the AGIE-machine is equipped with four machining units (C1, C2, C3 and C4) working independently. Each one of them has a special

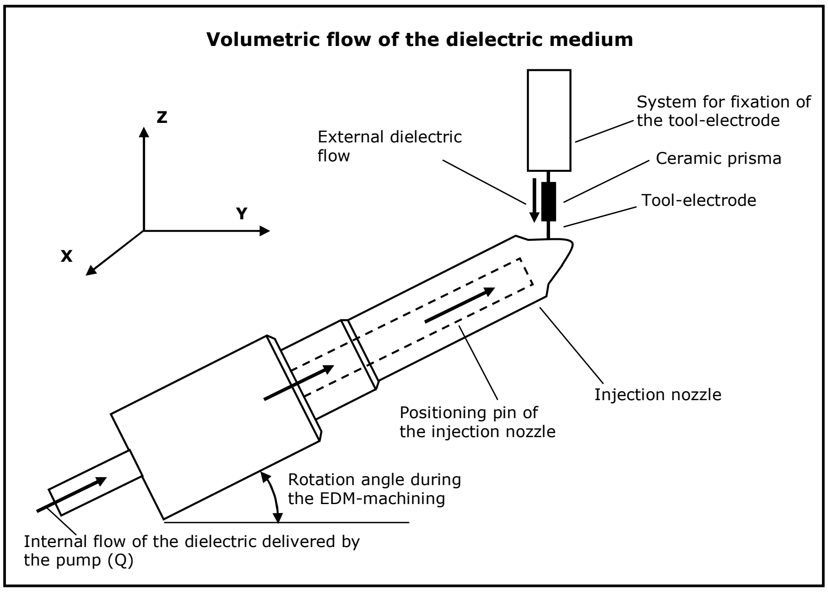

Fig. 3: Internal and external dielectric flow during the EDM-machining of a micro hole

system for the adequate positioning of the tool-electrode and injection nozzle (electrodes), being that the electrical energy of the electric discharges necessary to perform the material removal of the workpiece is obtained by a special type of "relaxation generator" of the AGIE Quadraton I. The generator parameters of the machining unit, acting together with the working gap monitoring system ("control system") consequently defines the material removal rate of the EDM-machining of a micro hole in the injection nozzle. This monitoring system has the function of rapidly detecting the presence of short-circuits during the machining that were generated through an elevated quantity of debris between tool-electrode and workpiece being machined. For the realization of the experiments of this article, parameter variations of the relaxation generator and control system of the EDM-machine (**table 1**) have not been made, only modifications of dielectric flow.

Fig. 2 shows the geometry of the injection nozzle type "DSLA" (18CrNi8 cemented, quenched and tempered) used in the experiments of this work. In this workpiece five micro holes were machined, in the injection nozzle seat. Each hole (with total length of 1 mm) has a defined position in the seat, characterized by two principal angles (ϕ and φ), also having an external and internal diameter, *DE* and *DI* respectively. For the EDM-machining of the micro hole the DLSA-nozzle is clamped precisely in the "mechanical fixation system of the workpiece" referring to machining unit C1. During the machining process the nozzle is rotated in a position so that the nozzle seat remains perpendicularly to the tool-electrode (**figure 3**). This rotation angle directly depends on the value ϕ and can be programmed by means of the open-loop controller of the AGIE-machine. Furthermore, an exact adjusting of the dielectric flow is important part of this machining procedure. Here there is a control of volume dielectric flowing externally at the tool-electrode (0,085 of diameter, consisted of tungsten) and internally in the injection nozzle. The internal volume (*Q*) of the deionized water (dielectric with electric conductivity of 0,5 mS/cm) is the process parameter to be experimentally investigated. The value of *Q* was modified by the dielectric pump in four different experimental levels (0; 0,04; 0,08; 0,11 g/sec) to verify the influence of this parameter on the diameter *DI* of the hole. For each adjusting of the dielectric flow five injection nozzles with 5 micro holes were machined. After the EDM-machining, for performing the one-way ANOVA analyze with application of the statistical software "Minitab 13", the external and internal diameter of these holes has been measured using an appropriate machine that executes measurements based on optical principles (model WEGU-Mycrona MPC, company Mycrona GmbH). Each

Table 1: Adjusting parameters of the AGIE Quadraton I

Parameters of the generator and control system to machine micro holes in injection nozzle		
Electronic unit	Parameter	Description
Relaxation generator	U (=250 Volts)	Voltage that creates an electric potential to provoke the "rupture" of the dielectric (deionized water), to generate electric sparks.
	Sbox (=45 µF)	Capacitor of the generator storing energy of an electric spark responsible for material removal. The increase of the Sbox (for example, to 55 µF), also using good conditions related to the volume of dielectric in the working gap, conduces to an elevated material removal rate, but normally to a higher tool-electrode wear.
	I (=2 A)	Electric current flowing into the capacitor with a defined capacitance (in this case, 45 µF).
	T (=10 µsec)	Total time correspondent to the current flow of 2 A into the capacitor. I and T define the electric energy stored in the capacitor (energy of the EDM-pulse).
	P (=8 µsec)	Time between two EDM-Pulses in sequence. The adjustment of this parameter determines the stability of the EDM-machining process. To perform the experiments of this work a time adjusting of 8 µsec between EDM-Pulses was made.
Control system (closed-loop control)	Com (=10 %)	The adjusting value of this parameter defines the frontal working gap dimension (for example, a variation of Com from 10 % to 50 % means a smaller distance (in µm) between electrodes (frontally)
	Gain (=40 %)	At a position deviation of the electrodes defined by the parameter Com the parameter Gain controls the velocity of the repositioning movement of the tool-electrode, so that the correct distance between them can reached again (relative to the Com 10 % previously adjusted).
Observation: - The adjusting of the above indicated parameter are made directly by the control panel (figure 1), using the open-loop controller of the AGIE-machine. - Normally during an electrically damped electric spark with a relaxation generator, the tool-electrode constantly assumes a positive and negative electric polarity. To avoid this, a diode was switch on in the electric circuit of the relaxation generator, thus enabling to make the EDM-machining of a micro hole only with tool-electrode polarized negatively.		

Table 2: One-way ANOVA of DI using the software Minitab 13

Result of variance analysis (F-Test)

One-way ANOVA: DI versus dielectric flow

Source	DF	SS	MS	F	p
dielectric flow	3	0,0000262	0,0000087	524,18	0,000
Error	8	0,0000001	0,0000000		
Total	11	0,0000263			

S = 0,0001291 R-Sq = 99,49 % R-Sq(adj) = 99,30 %

Observations:
- p-value < 0,05 indicated in the analysis of variance confirms that the variation of dielectric flow has an importance influence on the diameter of micro hole;
- R-Sq= 99,49 % indicates the reliability grade of the analysis of variance to the experimental data.
- S= standard deviation of the F-Test (F)

produced hole was measured five times to minimize the measurement uncertainty of obtained results, to accomplish the ANOVA with high reliability.

3. RESULTS AND DISCUSSIONS

The one-way ANOVA (analysis of variance or "F-test") with Minitab (Fernández, 2011; Franco, 2009) using a significance level of 5 % ("p-value") indicates that the variation of the dielectric flow within the proposed experimental field has an statistically significant influence on the diameter *DI* of the micro hole machined with the EDM-process. The **table 2** presents the results of this statistical analysis with their respective descriptions of DOE.

Fig. 4 presents the variation effect of dielectric flow on the internal diameter of the micro hole. Here it can be seen that the *DI* reduces enhancing the dielectric volume. The curve of the graphic presented in this figure can be mathematically identified by a regression equation (Mathews, 2004) based on a linear model (Eq.1). With this equation, and using a limit of a function, the informations of **figure 4** are described in according to the Eq. 2. The variations of *DI* (0,123–0,127 mm) verified in this figure cause great modifications of the geometrical form of a micro hole machined (**Fig. 5**), having immediate consequences of the functional characteristics of the injection nozzle in operation condition. In dependence on the practical application of the nozzle a conicity of the hole is desired ("k-factor injection nozzle"), because of the fact that with this geometry a special condition of fuel spray being injected can be reached to optimize the combustion process in the motor's chamber, thus reducing the emissions of pollutants and fuel consumption of the vehicle. The technical reliability grade of the motor is directly dependent on the geometry of the injection hole machined with the EDM-technology.

$$DI = -0{,}0353(Q) + 0{,}1268 \qquad R^2 = 0{,}9776 \qquad (1)$$

$$\lim_{Q \to 0{,}11} DI(Q) = 0{,}123 \Rightarrow \lim_{Q \to 0{,}11} [(0{,}0353(0{,}11) + 0{,}1268] = 0{,}123 \qquad (2)$$

here, DI= internal diameter of the micro hole; Q= dielectric flow; R^2= coefficient of determination of the regression model.

In the **figure 6** it can be identified what occurs in the exact moment relating to the "rupture" of micro hole being machined. After this rupture process the tool-electrode still moves forward until reaching the maximal programmed machining depth in the open-loop controller system of the EDM-machine. In this case the total depth was adjusted in -1,5 mm, related to coordinate axis "z" presented in the **figure 3**. Generally the resulting debris of the EDM-machining progressively tends to accumulate in those regions of the hole referring to the deepest positions of the tool in the micrometric cavity being produced. The hole rupture now enables that internal dielectric flow acts in the machining procedure. This flow drastically reduces an accumulation of EDM-process particles in high machining depths, where here there is also a considerable minimization of the quantity of short circuits between electrodes. The tool-electrode displacement occurs more rapidly, consequently improving the material removal rate of the machining process due to the few actuations of the closed-loop controller of the EDM-machine to correct process deviations. Alterations of the material removal rate normally mean that the geometry of the micro hole can be modified. Moreover, the possibility to apply the internal flow of dielectric at the moment of hole rupture has the advantage of introducing a dielectric volume with high grade of purity in the deepest areas of the EDM-machining process. This elevated quality defines a work medium having high insulating properties (small electric conductivity), what improves the geometrical precision of hole diameter, internally. This precision can be indentified, for example, through a perfect diameter circularity which has a great importance in the fuel injection process of a motor. Simulation techniques of fluid mechanics are used today successfully to verify the influence related to the diameters' geometry (*DE* and *DI*) of micro hole on the characteristics of a diesel motor injection. The results of these simulations make it possible in some cases to perform adjustments of EDM-parameters for obtaining the best quality related to the diameter of the machined injection hole. The correct stability of the EDM-process at the moment of the hole rupture is decisive to obtain the exact geometry of the DI, what certainly can be achieved by the optimized adjusting of

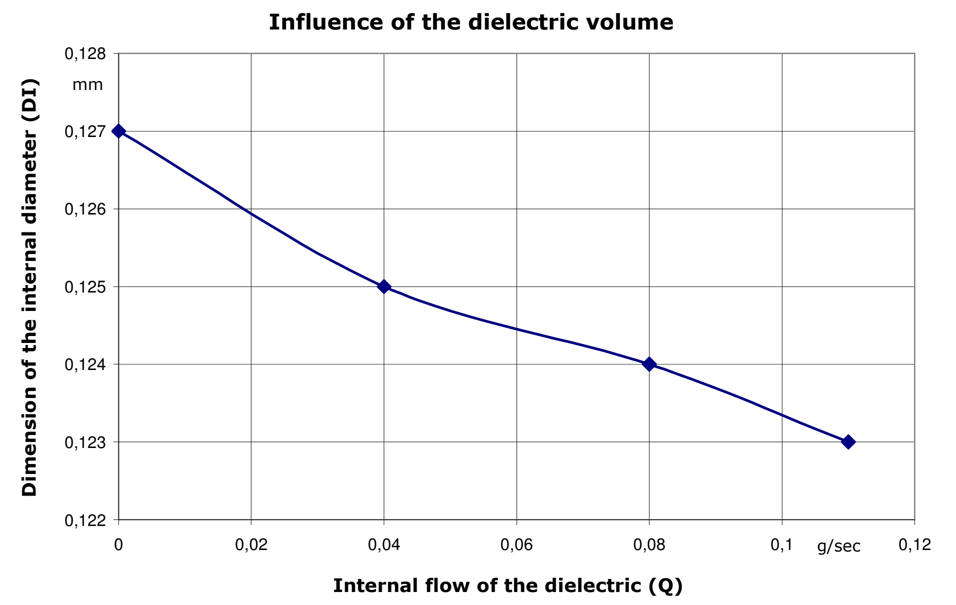

Fig. 4: Influence related to the variation of dielectric volume on DI

the internal dielectric flow. Fine optimizations of the diameter form are also possible through specific adjustments of the generator parameters of the tool-machine in combination with a defined volume relating to the internal flow of dielectric, using adequate methodologies of the design of experiments (specially here full or fractional experiment, in dependence on the total number of those EDM-parameters being experimentally investigated) to statistically identify interactions of EDM-parameters (Souza, 2000 and 2012). In these experiments the establishment of a low level of vibration of the tool-electrode is very important to avoid great influences on the internal diameter of the micro hole. For example, there is an accentuated increase of this vibration level by applying an elevated distance of penetration of the tool (*p*) in workpiece being machined after the hole rupture, where normally in the practice a considerable enlargement of *DI* is expected. The vibrations in the EDM-machining are also more intensive by the use of tool-electrodes with very small diameters (*d*) or having a material constituted of a reduced elastic modulus (*E*). In other words, the same effect on the internal hole diameter using *Q* in high adjustment values is possible by increasing the variables *d* and *E* as well as diminishing *p*.

The increase of the internal dielectric flow produces a “displacement zone” of work medium from the hole's surface (**figure 7**), creating here a region with flow turbulences and consequently having great volumetric quantities of gases. This condition within the lateral working gap so tends to generate there electrical discharges which prejudice the surface of the micro hole. The greater the internal flow of the dielectric, the higher is the probability to be produced these discharges during the EDM-process as consequence of the enormous expansion of the above mentioned zone. Thus, this is one important cause of the continuous augment of the dielectric quantity in the machining process of a micro hole. The other effect of this increase is that there is a great difficulty in developing a plasma channel in the frontal space between the tool-electrode and workpiece being machined at the moment the hole's rupture. Very high values of *Q* diminish the chances for generating electric sparks, or provoke the formation of them with a great ignition time (“Zündverzögerungszeit”) (Souza, 2009), as direct cause of the non-complete ionization process of the plasma to correctly develop an electric discharge. In other words, the elevated profile velocity of the work medium at the internal diameter of the micro hole impairs the phenomena related to the impact ionization of the deionized water in the frontal working gap, what

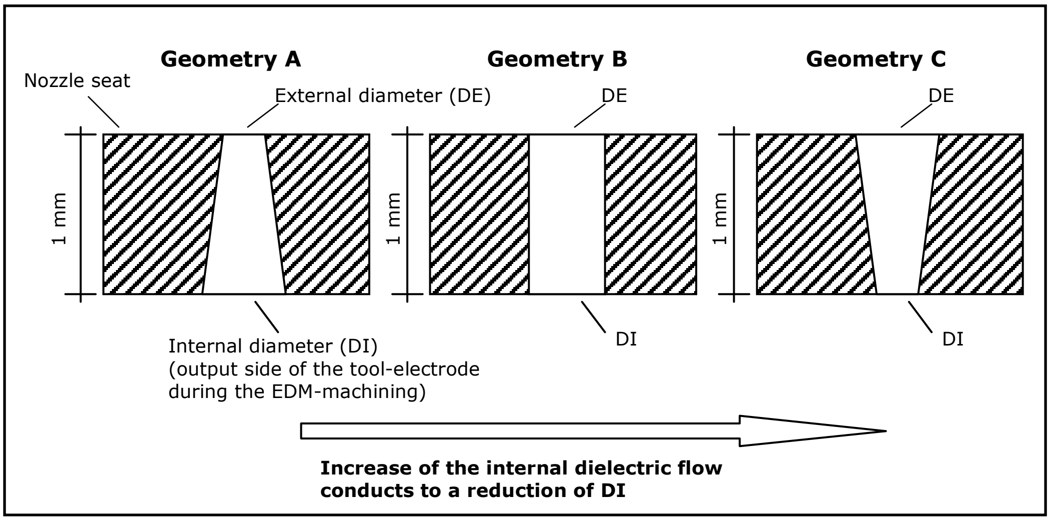

Fig. 5: Alteration of the micro hole geometry (conicity) increasing the dielectric flow

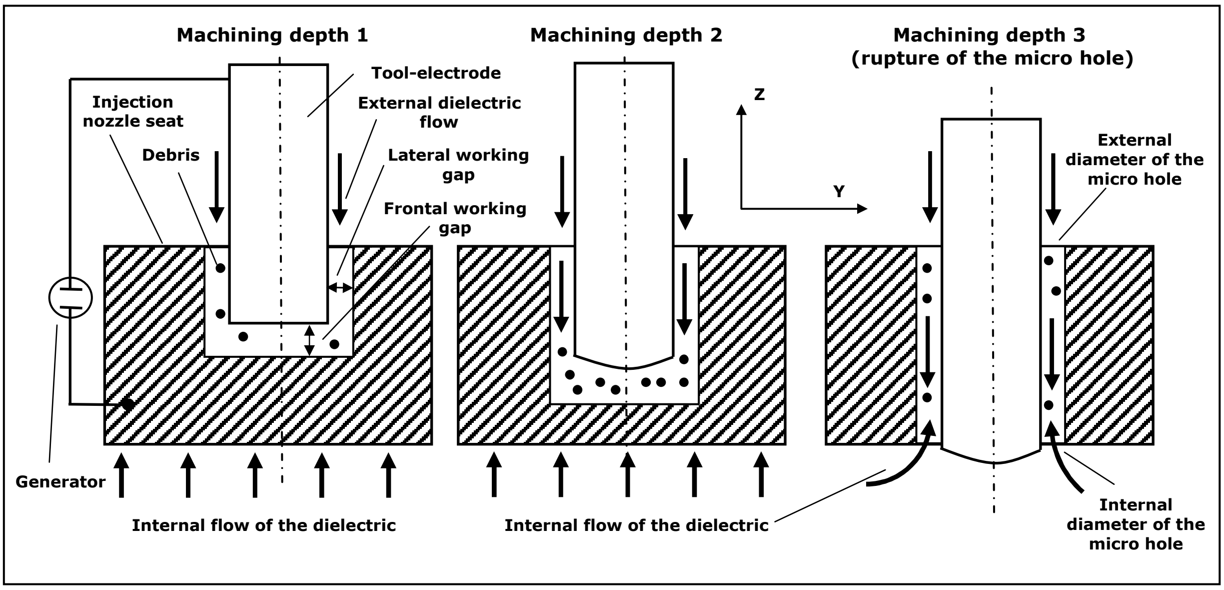

Fig. 6: Influence of internal dielectric flow at the moment of “hole rupture”

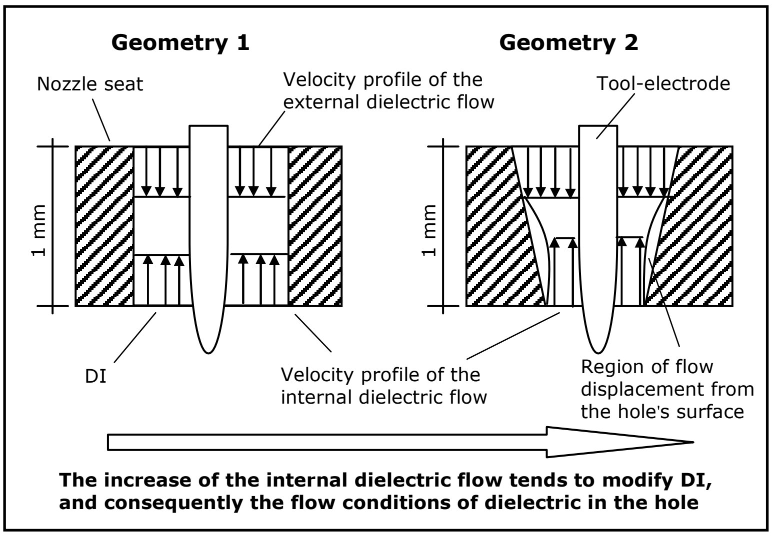

Fig. 7: Different velocity profiles of the work medium in dependence on the hole conicity

conduces to the development of an electric spark with an extremely small energetic content. The negative result of this is the reduction of material removal rate of the EDM-process, consequently generating an injection hole with reduced *DI*. A precise ignition time of the spark is main factor to develop a correct volume of the plasma channel within the exact time period (dV_{PL}/dt) (Eq. 3) desired to bring about a sufficient melting of the workpiece, thus producing an optimized rate of material being machined. This melting process is characterized by the appearance of a discharge crater in the workpiece surface, directly proportional to the plasma channel volume (Roth, 2001), with defined thermal energy (reaching temperatures of approximately 10000 °C) that is also limited through the electronic adjustments of the generator of the EDM-machine. Any instability of the EDM-machining, as for example, an adjusting of the internal dielectric flow at values of 0,11 g/sec, causes modifications of the electric discharge energy, causing a decrease of the crater's volume in the electrodes' surface. This volume reduction has a positive advantage for the EDM-machining, due to the fact that a minor amount of electrically conductive debris is generated within the working gap conducting to undesirable short circuits, so rising the EDM-machining time.

$$\frac{dV_{PL}}{dt} = \frac{\partial V}{\partial x}\frac{dx}{dt} + \frac{\partial V}{\partial y}\frac{dy}{dt} + \frac{\partial V}{\partial z}\frac{dz}{dt} \qquad (3)$$

in this case, dV_{PL}/dt = variation of the plasma channel volume of an electric discharge at time in dependence on three coordinate axes (x, y and z), after the complete breakdown of the dielectric strength to produce this discharge.

Generally the use of high values of *Q* generates strong vibrations of the tool-electrode, where this is certainly more expressive by using very fine tool diameters, as in the case of the experimental conditions presented in this paper. During the EDM-machining of the micro hole the tool can be seen as a “cantilever beam” (Tjahyadi and et. Al, 2004) which vibrates in according to a resultant force intensity [($F(y,t)$] normally of non-harmonic character and acting with a defined frequency in its end, generated through a force disequilibria induced by the elevated velocity of the internal dielectric flow (**Fig. 8**) in combination with the presence of removal products in the working gap. These forced vibrations, and with damped characteristics (Gyu, 2003) (because of constant contact of the dielectric at the lateral surface of the tool-electrode), cause considerable irregularities in the geometrical form of the internal hole diameter. Certainly the critical situation related to the vibration level, which can produce high quality problems in the *DI*, is the case that the acting force $F(y,t)$ conducts the tool-electrode to a resonance frequency, where here an elevated vibration amplitude is achieved in the EDM-machining after a specific period of time from the moment relating to the hole rupture. This high vibration can also cause more easily a mechanical contact of the tool with the hole wall, thus conducting the closed-loop controller of the EDM-machine to clearly identify this as a short circuit, consequently reducing the material removal rate of the electrical discharge machining process, because of a greater time to machine the injection hole. To exactly verify this vibration level and perform its minimization it is necessary to assemble at the fixation device of the tool-electrode a precisely calibrated measurement technology using piezoelectric accelerometer (Hongli, 2010) connected to an appropriate data acquisition system. With this it is technical possible to make correct adjustments of the internal dielectric flow aiming to obtain the desired hole geometry by reducing extremely high vibration intensities in the EDM-process. The perfect comprehension of the origin of these vibration sources (identifying here the respective vibration modes of the system as consequence of the intensity of *Q*) facilitates the development of models with use of finite element method (Liu, 2003) to optimize, for example, the tool-electrode fixation within the z-axis of the EDM-machine. In general, the tool's vibration previously mentioned can be described by Eq. 4. This differential equation is based on the theory of Euler-Bernoulli (Botega and et. al, 2007), assuming here that the damping grade of the beam caused by the contact of the

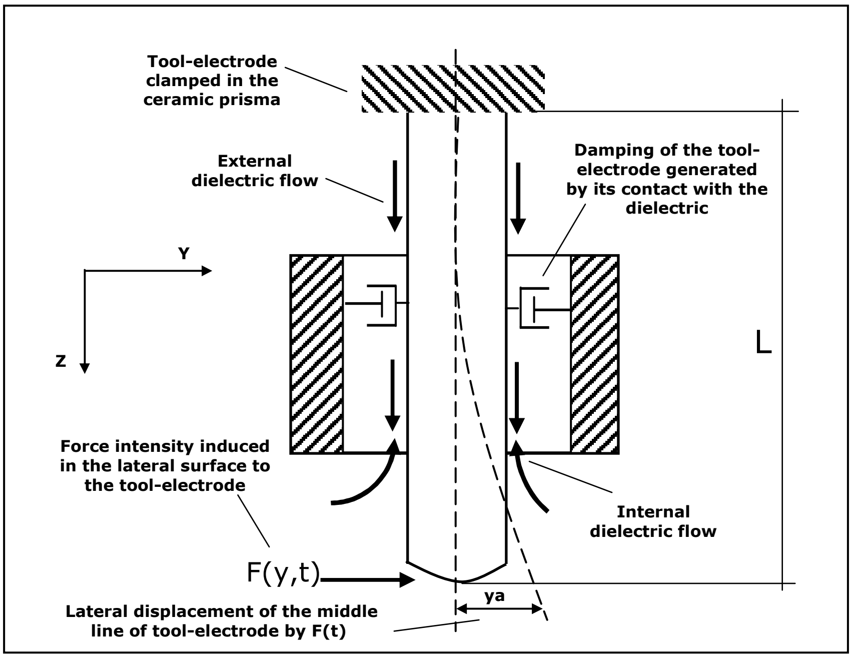

Fig. 8: Vibration force produced on the surface of the tool-electrode at the moment of hole rupture

dielectric "with the lateral surface of the tool-electrode" is practically zero. The respective boundary conditions (Silva, 2000) for the mathematical solution of this equation are also here presented. Furthermore, the function *h(t)* of Eq. 5 can properly assumes a periodic, aperiodic or stochastic form, which could be mathematically formulated by an appropriate model. Elevated amplitudes of this time function instantly produce tensile and compressive stresses in the tool-electrode material within an elastic condition, throughout the electrode length.

$$\frac{\partial^4 y(z,t)}{\partial z^4} + \frac{\rho A}{EI} \cdot \frac{\partial^2 y(z,t)}{\partial t^2} = F(y,t) \qquad (4)$$

$$y|_{z=0} = 0; \quad \frac{\partial y}{\partial z}|_{z=0} = 0; \quad M(L,t) = EI(z)\frac{\partial y^2(z,t)}{\partial z^2}|_{z=L} = 0;$$

$$Q(L,t) = -\frac{\partial}{\partial z}[\frac{EI(z)\partial y^2(z,t)}{\partial z^2}|_{z=L} = F(y,t);$$

$$F(y,t) = Y(z).h(t) \qquad (5)$$

where, EI= beam rigidity (E= Young's modulus and I= moment of inertia of the cross-sectional area of the beam); ρ= mass density; A= cross-sectional area of the beam; F(y,t)= function of force intensity acting at the end of the beam relative to the length L, induced by the application conditions of the internal dielectric flow Q during the EDM-process; t= time; y(z,t)= vertical displacement of the beam at a position z of the tool-electrode and at the time t; Y(z)= function describing the beam's deflection in a position z; h(f)= a mathematical function of time; Q= shear force acting in a defined point z of the tool-electrode; M= bending moment at a position z of the electrode.

4. CONCLUSIONS

This experimental result clearly indicated the strong influenced of the internal dielectric volume on the geometrical characteristics of holes produced with the electrical discharge machining, being in this case a very important process parameter to be precisely controlled in the production line of an industry related to the manufacturing of injection nozzles with special applications for injection systems. The perfect control of the dielectric flow in the EDM-machining consequently avoids excessive part defects as well as conducts the EDM-process to a correct machining time, thus ensuring a reduction of fabrication costs of the manufacturer of injection nozzles. In dependence on the injection nozzle geometry there is a necessity to adjust a defined dielectric volume so that the best work result can be achieved, according to the adjustment of other EDM-parameters of the tool-machine to perform the material removal of the injection hole with a low vibration level of the tool-electrode.

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