Variation effect of parameters related to the closed-loop control of the EDM-machine on the hydraulic flow and microhole diameters of injection nozzles constructed with steel 18CrNi8

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Abstract:

The main paper's objective is to present experimental results that basically consist in verifying the influence of the controlled variation of parameters of the closed-loop system of an EDM-machine on the work result of the machining process: hydraulic flow and diameter dimension of microholes machined in injection nozzles DSLA constructed with steel 18CrNi8 in cemented condition of heat treatment. These experiments are performed using a tool-machine of the manufacturer AGIE Charmilles, applying tool-electrode of tungsten with diameters of 0,085 mm, where in this case small holes (with diameters smaller as 0,14 mm) have been machined in the above mentioned nozzles through the electrical discharge machining, with use of a specific adjustment of two principal parameters of closed-loop control system of the machine (Gain and Com - velocity of the "repositioning movement" of the tool-electrode and distance between electrodes in the "frontal working gap", respectively) under utilization of deionized water with extremely low electrical conductivity as dielectric medium of the EDM-process. The experimental results indicate that these EDM-parameters differently affect the work result, that is, hole diameter and hydraulic flow of the injection nozzle, according to a pre-defined machining depth of the tool-electrode in the microhole being machined.

Keywords: Closed-loop control system, EDM, electrical discharge machining, microhole, injection nozzle, 18CrNi8

1. Introduction

One of the most important points to reduce the emission levels of a diesel motor with common rail system is certainly the geometrical quality related to the microholes of injection nozzles. This quality is characterized in the practice by the diameter precision and capacity of hydraulic flow of the holes. Both characteristics are clearly responsible for conducting the correct volume of combustible into the motor combustion chamber to obtain the exact ratio fuel/air. The above mentioned quality is guaranteed by the perfect adjustment conditions of the machining process used to produce the microholes, in this case, of the EDM-technology (electrical discharge machining). Today this process is successfully applied in the manufacturers of injection components for the automobile industry to precisely machine holes in specific types of steels (as for example, the material 18CrNi8) with special EDM-machines. The electronic and mechanical construction of an EDM-machine also defines the final geometry of these holes. In this case the closed-loop control of the EDM-machine is extremely crucial to maintain the desired stabilization of the EDM-prozess of a microhole being machined, especially because the fact that in this production prozess a tool-electrode with very fine diameter is used. Thus, with the optimized adjusting of parameters relating to the machine closed-loop control it is possible to reach the best geometry of the microhole. Normally this indicates that the machined hole will probably satisfy its characteristics of hydraulic flow (explained in the sequence of this paper) required for the proper functioning of the injection nozzle in an engine.

The next chapters of this article are connected with the presentation of experimental results related to the analysis of the influence of close-loop control parameters of an EDM-machine on the diameter and hydraulic flow of microholes machined in injection nozzles. In these experiments two main variables of the close-loop control system (“Com” and “Gain”) are simultaneously modified in according to a defined machining depth of the tool-electrode in the microhole being produced using the electrical discharge machining process. For a precise verification of the experiments' result special measurement technologies were used, whose principal technological features are also presented in the details in the paper’s content. A detailed description of all mechanical and electronic characteristics of the tool-machine presented in the paper (especially of the generator of this equipment) is necessary for a profound comprehension of the practical and theoretical explications of the performed experiments that are given in the chapter “Results and Discussions” of this article.

2. Experimental methodology

2.1 Mechanical and electronic features of the EDM-machine used in the experiments

For the realization of the experimental analyses a modern EDM-machine of the manufacturer AGIE Charmilles (model AGIE Quadraton I) (**fig.1**) has been used. This equipment was particularly developed to produce microholes (having diameters smaller as 0,5 mm) in injection nozzles with use of the EDM-prozess, applying electric discharges of extremely low energy for material removal during the machining process. Basically this machine consists of mechanical systems for fixation and positioning of the electrodes (tool-electrode and injection nozzle), relaxation generator working in combination with a control-loop control system as well as a system to adjust and control the temperature (in 15 ± 3 °C) and electrical conductivity (approximately 0,5 mS/cm) of the dielectric medium (deionized water). For example, this reduced value of conductivity is a very important process parameter which is adjusted by the physical-chemical properties of an ion-exchange resin and controlled within close limits through an EC meter. The dimension precision of a microhole produced with the EDM-technology directly depends on this conductivity value. Small dielectric conductivity also means a narrow working gap (laterally and frontally, relating to the space separating two electrically polarized surfaces during the EDM-machining of a hole with micrometric dimension), where here the dielectric consequently presents a high resistance as liquid insulator substance.

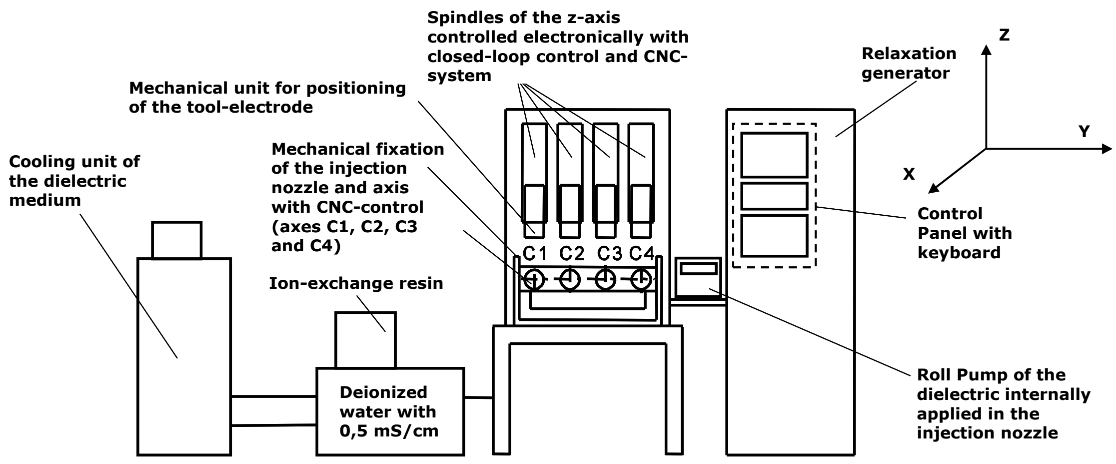

Fig.1: Main technological characteristics of the machine AGIE Quadraton I used in the experiments

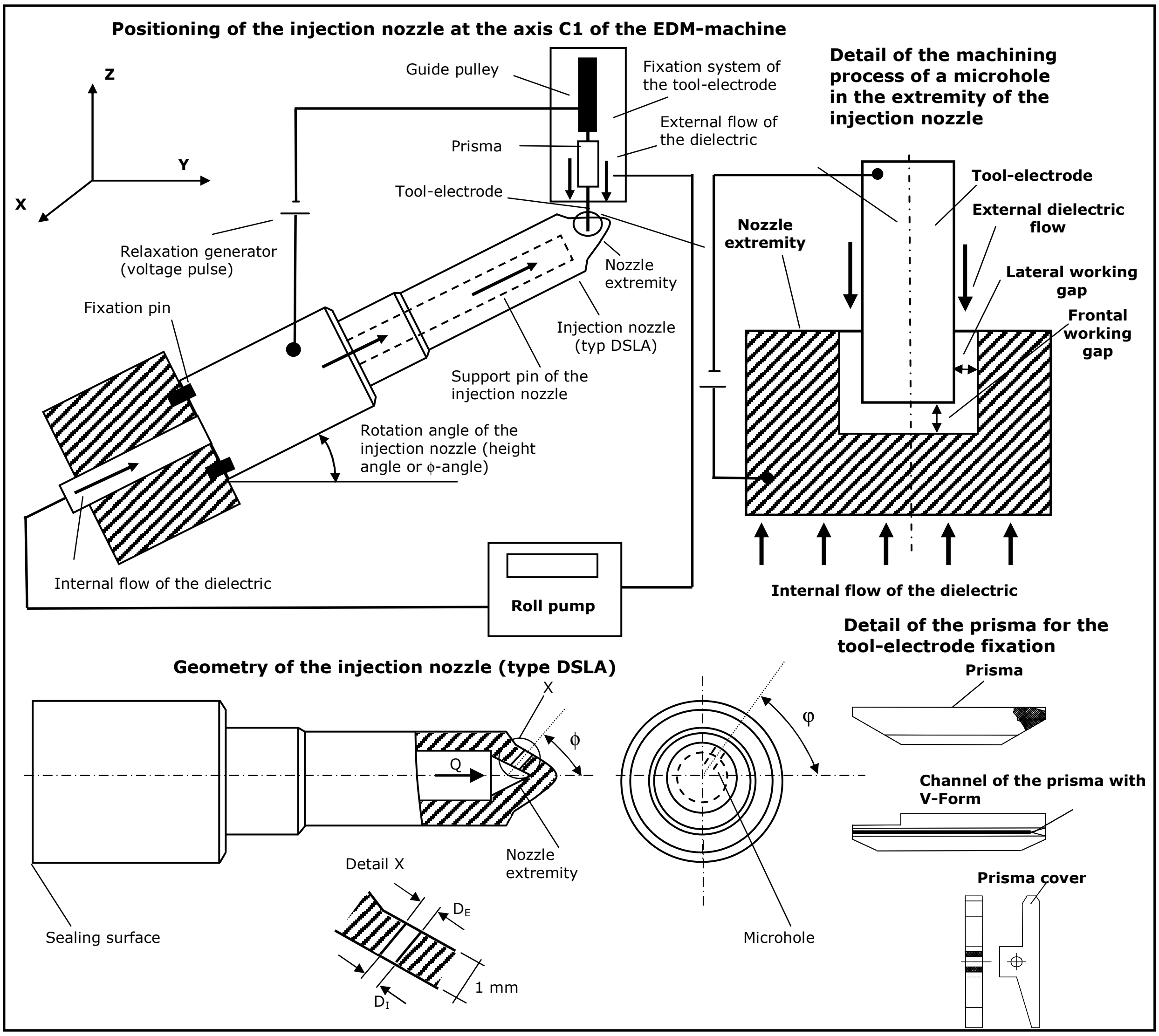

Fig.2: Positioning of the injection nozzle (workpiece) at the axis C1

Fig. 2 presents the fixation system of an injection nozzle positioned in the machine AGIE for the machining process. Basically, this mechanically precise system consists of an axis (for example, the C1) executes a pre-defined rotation angle (ϕ-angle) around the X-axis (see orientation of the coordinate system indicated in **figure 2**). Beyond this the nozzle normally has an angular movement around the Y-axis (φ-angle – not indicated in this figure), as well as a small displacement in this machine axis, both movements are necessary to defined the correct geometrical position of a microhole in the injection nozzle. Furthermore, during the EDM-machining of the hole, the tool-electrode (with diameter of 0,085 mm and chemically constituted of tungsten) moves along the Z-axis. The exact position of the electrode in this axis is ensured by the prisma (produced from ceramic material with elevated resistance to high temperatures and friction) which presents a cavity (channel) with a special geometry. The lateral surface of the tool-electrode is in contact with the prima's channel (and also pressed in this channel with a very controlled force through the “prisma cover”, thus reducing the tool-electrode vibration during the EDM-machining). For execution of the machining process a reduced quantity of dielectric medium is flowing externally at the tool-electrode surface to eliminate the removal products from the working gap, avoiding the appearance of short circuits which can conduct to a high machining time and consequently to a low material removal rate of the microhole being machined. The internal flow of the dielectric properly acts in the moment of the “hole rupture” (when the microhole becomes a “through hole”). This dielectric flow internally applied in the injection nozzle (at the nozzle extremity by the roll pump) has the main function of controlling the final dimension and geometric contour of the internal hole diameter (DI – see Detail X in **figure 2**). The difference of DE and DI identifies a microhole's conicity that in some cases (relating to the technical application of nozzle) can be desired totally. The hole length resulting after the EDM-machining is 1 mm.

2.2 Adjusting parameters of the relaxation generator and control-loop control of the EDM-machine

The relaxation generator is undoubtedly one of the most important components of the AGIE-Quadraton I. This generator has different possibilities to be adjusted so that an optimized control of energy as well as stability of the EDM-prozess can be achieved for the best work result related to the microhole machined (see descriptions of the adjusting parameters of this electronic unit in the **table 1**). Certainly the correct operation condition of the electrical discharge machining depends on the adjustment of the generator's parameters in combination with those relating to the closed-loop control system (Com and Gain). The closed-loop control parameters have a high influence on the machining stability and also on the geometric form of the machined microhole. The experiments of this paper are directly related with the investigation about the variation effect of Com und Gain on the geometry and hydraulic flow of microholes produced with the EDM-machining. Depending on a specific adjustment condition of these process parameters a special hole geometry can be obtained (according to the forms presented in **Fig. 3**) Each one of these geometric forms plays an extremely important role in controlling the total hydraulic flow of a microhole. The total dimension of DE and DI (and the hole conicity resulting of the these two diameters) is connected with the final value of this flow.

Table 1: Adjusting parameters of the AGIE Quadraton I

Parameters of the generator and closed-loop control system to machine microholes in injection nozzle		
Electronic unit	Parameter	Technical description
Relaxation generator	U-I (normally 180 to 240 Volts)	Electrical voltage applied at the electrodes to produce the "rupture" of the dielectric. The voltage intensity also has a small influence on the energy of the electric discharge produced in the working gap. High values of U produce the enlargement of the space between the tool-electrode and workpiece being machined.
	Sbox (=50 µF) (Capacitance of the capacitor)	This parameter controls the total energy of the electric discharge. High value of Sbox (together with good conditions relating to the elimination of debris from the working gap) normally conduces to an elevated material removal rate, but has as disadvantage the formation of an elevated wear of the tool-electrode.
	I (=1 A)	Load current of the capacitor electrically adjusted with a value of capacitance in µF (for example in 50 µF)
	T (=5 µsec)	Load time of the capacitor. For example, the parameter T with adjustment in 5 µsec means that the capacitor will be loaded with a current of 1 A during a time period of 5 µsec.
	P (=10 µsec)	Total time between two electric discharges. The decrease of P increases the frequency of sparks and produces a great material removal during the EDM-machining processes with good flushing conditions in the working gap.
Closed-loop control system	Com (=20 %)	Adjusting of dimension of the frontal working gap between tool-electrode and workpiece. The higher the value of Com, the smaller is this dimension.
	Gain (=10 %)	The value of the Gain defines the repositioning velocity of the tool-electrode in case of the presence of short circuits within the working gap. High values of Gain indicate that the tool-electrode makes a rapid repositioning movement to eliminate process deviations (short circuits).

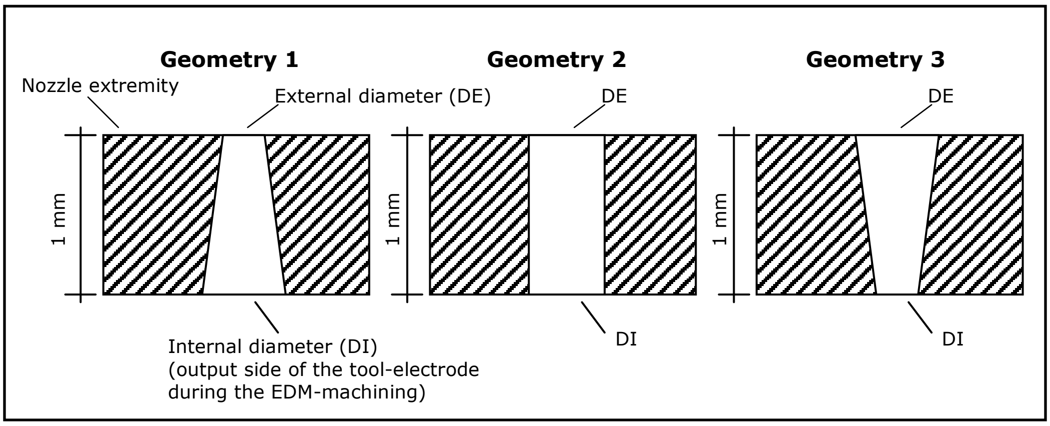

Fig. 3: Possible geometries of microholes in the injection nozzle according to an adjustment of Com and Gain

2.3 Measurement of microhole diameter and hydraulic flow of the injection nozzle

The diameter determination of the machined microhole was made by use of a measuring machine model WEGU. With this equipment the DE and DI can be precisely determined using optical principles together with application of coordinate measuring techniques. The machine automatically calculates the hole conicity and also gives the spatial position (angles ϕ and φ) of each hole in the nozzle extremity. In the experiments of this article injection nozzles with 5 microholes were produced using tool-electrode with diameter of 0,085 mm, where in this case the WEGU-machine can be correctly programmed to perform the measuring process of these holes. Moreover, to complete the evaluation procedure of the experimental analyses and obtain further informations related to the geometric shape of the machined holes, measurements of hydraulic flow of the injection nozzle after the machining were conducted by an equipment especially constructed for this purpose. The determining process of this flow (giving in cm^3/30sec) basically consists of the introduction of a special oil (having a defined viscosity and temperature) through the nozzle with pressure adjusted in 100 bar (**fig. 3**). Each one of the machined microholes presents a specific hydraulic flow (for example, Q1 referring to the microhole 1). The sum of the individual flows of the holes consequently gives the total flow Q of the injection nozzle.

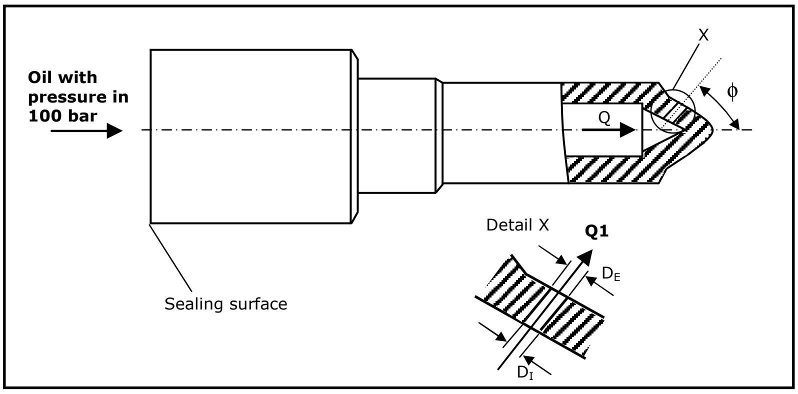

Fig. 3: Measuring procedure of the hydraulic flow of an injection nozzle after the machining process

2.4 Experimental design

The machining process of a microhole in the injection nozzle is made in five steps (**table 2**). Each one of these steps corresponds to defined machining depths ("W") of the tool-electrode in the workpiece being machined and can be adjusted with a specific group of machining parameters. For example, the step 1 occurs until a machining depth of 0,2 mm, where in this case the tool-electrode is negatively polarized (see parameter "U" of the table) so that a "dressing process" of the its extremity can be made to enhance the dimensional precision of the hole. After this depth the tool-electrode polarity is thus inverted to conclude the EDM-machining in four remaining steps. Each machining depth takes place under a special adjustment of process parameters related to the closed-loop control system of the EDM-machine (Com and Gain). The experiments proposed in this paper are connected with the variation of these parameters and their effects on the internal diameter of the produced microholes and hydraulic flow of injection nozzle. This modification (both EDM-parameters were here varied in 3 different experimental levels, with four replicates in the respective experimental level) has been executed in the machining steps 3, 4 and 5, as presented in the **table 3**. In other words, for each step a "Two-Way ANOVA experiment" has been conducted, consequently resulting in a total of 108 performed experiments.

Table 2: Adjusting parameters to machine a microhole in different machining depths

Nr.	W	U (tool-electrode polarity)	I	U-I	T	Sbox	P	Com	Gain
[-]	[mm]	[+ or-]	[A]	[Volts]	[µsec]	[µF]	[µsec]	[%]	[%]
1	-0,2	+	1	223	0,4	30	9	30	8
2	-1,3	-	1	187	0,4	44	9	30	8
3	-1,6	-	1	187	0,4	44	9	30	8
4	-2,2	-	1	187	0,4	44	9	30	8
5	-2,55	-	1	187	0,4	44	9	30	8

OBS:
- Parameters' description of the relaxation generator and closed-loop control in according to the table 1;
- "Nr." identifies the different machining steps.

Table 3: Variation of Com and Gain in different experimental levels according to the machining depth

Nr. 3			**Gain**		
			4 %	8%	12 %
Step 3 (-1,6 mm)	**Com**	20 %	4 replicates	4 replicates	4 replicates
		30 %	4 replicates	4 replicates	4 replicates
		40 %	4 replicates	4 replicates	4 replicates

Nr. 4			**Gain**		
			4 %	8%	12 %
Step 4 (-2,2 mm)	**Com**	20 %	4 replicates	4 replicates	4 replicates
		30 %	4 replicates	4 replicates	4 replicates
		40 %	4 replicates	4 replicates	4 replicates

Nr. 5			**Gain**		
			4 %	8%	12 %
Step 5 (-2,55 mm)	**Com**	20 %	4 replicates	4 replicates	4 replicates
		30 %	4 replicates	4 replicates	4 replicates
		40 %	4 replicates	4 replicates	4 replicates

3. Results and discussions

The graphics of the figure 3-A, 3-B and 3-C show the results related to the experimental planning in indicated in the **table 3**. For all machining depths a behavior totally random of the output-variables being analyzed can be verified with the controlled modification of the parameters Gain und Com. This alteration conducts to a better or worse stabilization of the machining conditions in the working. In other words, the variation of the control loop control parameters of the EDM-machine is responsible for a greater or lesser presence of the short-circuits during the electrical discharge machining, what directly reflects in the machining time to produce a microhole. This time is significantly modified through the modifications of the above mentioned EDM process parameters, where here an influence on the material removal rate of the EDM-machining is expected, with technically considerable alterations in the geometric form of the machined hole. Com and Gain work together, that is, a variation of one of these input-variables is inevitably conditioned to a correct adjusting of the other process parameters to obtain the desired result of the output-variable being studied in the experiments. **Fig. 5** presents a theoretical description of how both EDM-parameters are dependently working in the closed-loop control system of the machine AGIE Quadraton I. Here the modification of Com from 50 % to Com 10 % means an increase of the total dimension of the frontal working gap between electrodes. The closed-loop control technique of the EDM-machine constantly tries to maintain the gap dimension (frontally) according to the conditions established through the adjustment of Com. Even happening an extremely small deviation from this position the parameter Gain thus acts in the machining procedure so that the electrodes' space can maintained once again. In this situation the acting process of Gain is the repositioning movement of the tool-electrode with a specific velocity. For example, the Gain-variation of 20 % to 60 % indicates that the repositioning velocity is very rapid, where also in some cases this has as consequence the generation of a high tool-electrode vibration, provoking a strong destabilization of the machining conditions and so with a considerable enhancing of the machining time, conducting to variations of the material removal of microhole. This vibration level certainly becomes more pronounced using tool-electrodes having fine diameters and reduced elastic modulus [1]. So it is desired to adjust Com and Gain in a combined form for obtaining the exact stabilization of the EDM-process by reducing short circuits as well as the tool-electrode vibrations, achieving in this way the best work result with application of tool with diameter of 0,085 mm. The obtention of a continuous movement of the tool-electrode (also, without the frequent interferences of the closed-loop control system) during the machining process is the principal factor to achieve the correct quality of the machined microhole.

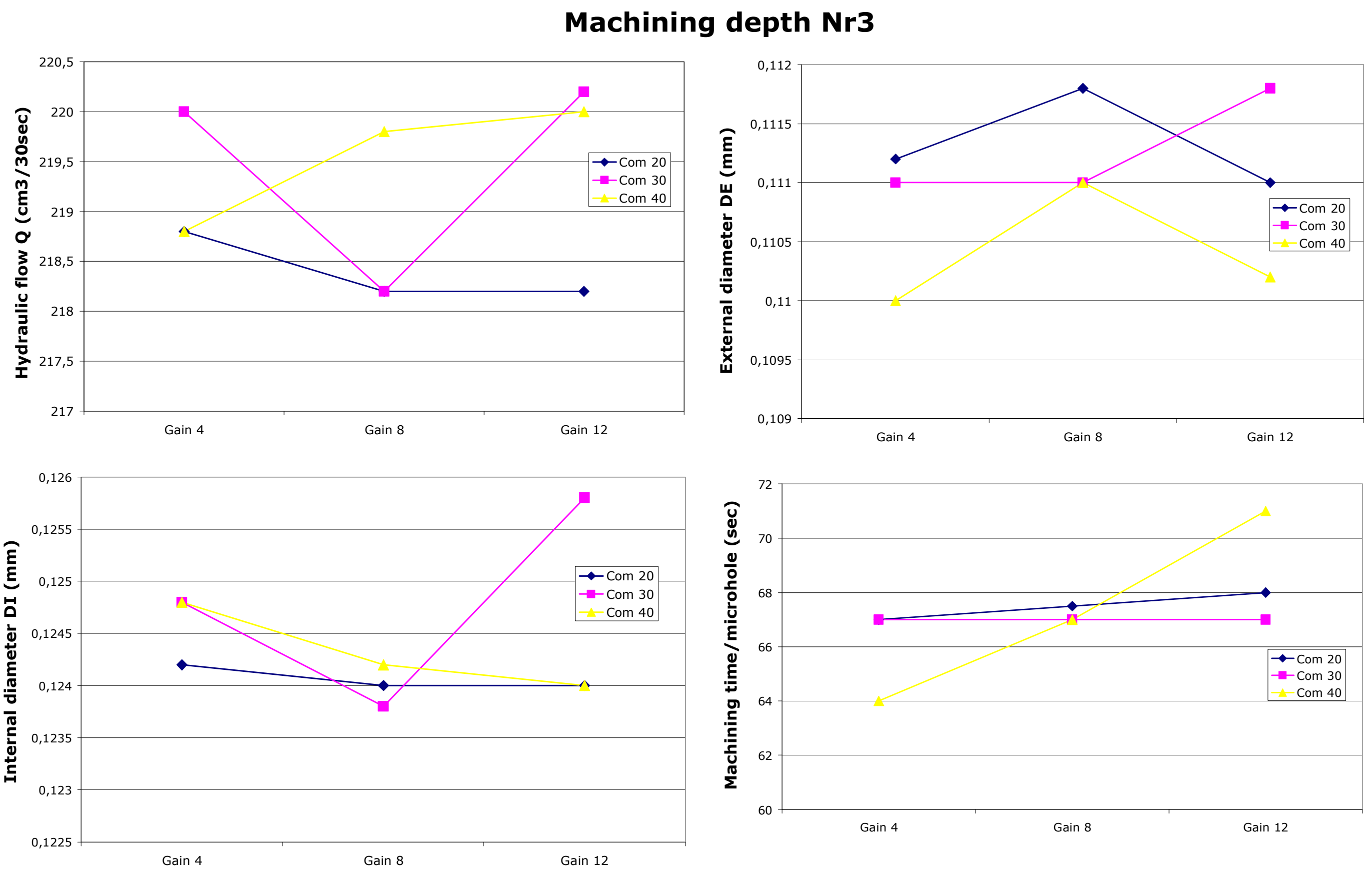

Figure 3-A: Experimental results related to the machining depth 3

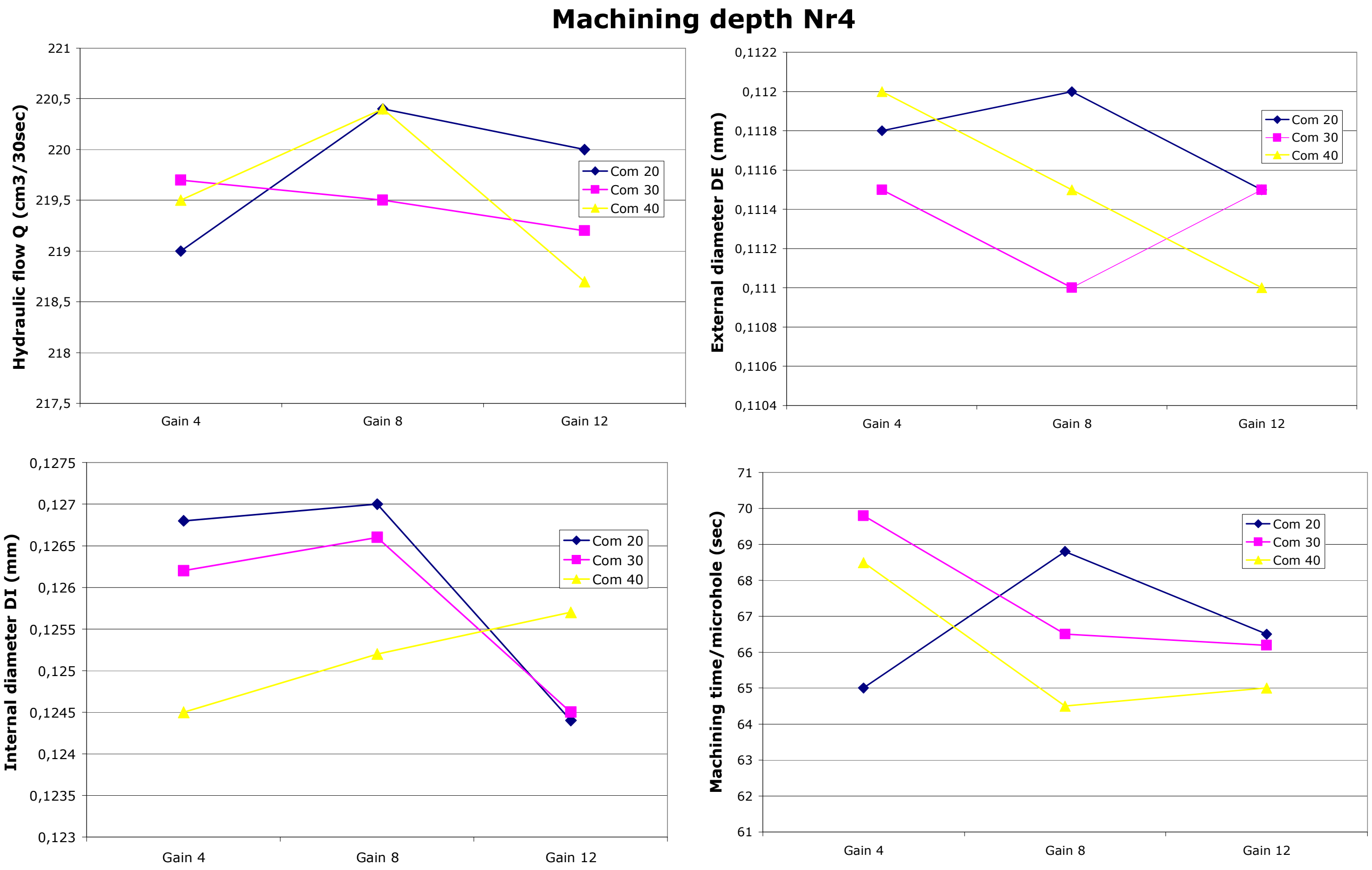

Figure 3-B: Experimental results relating to the machining depth 4

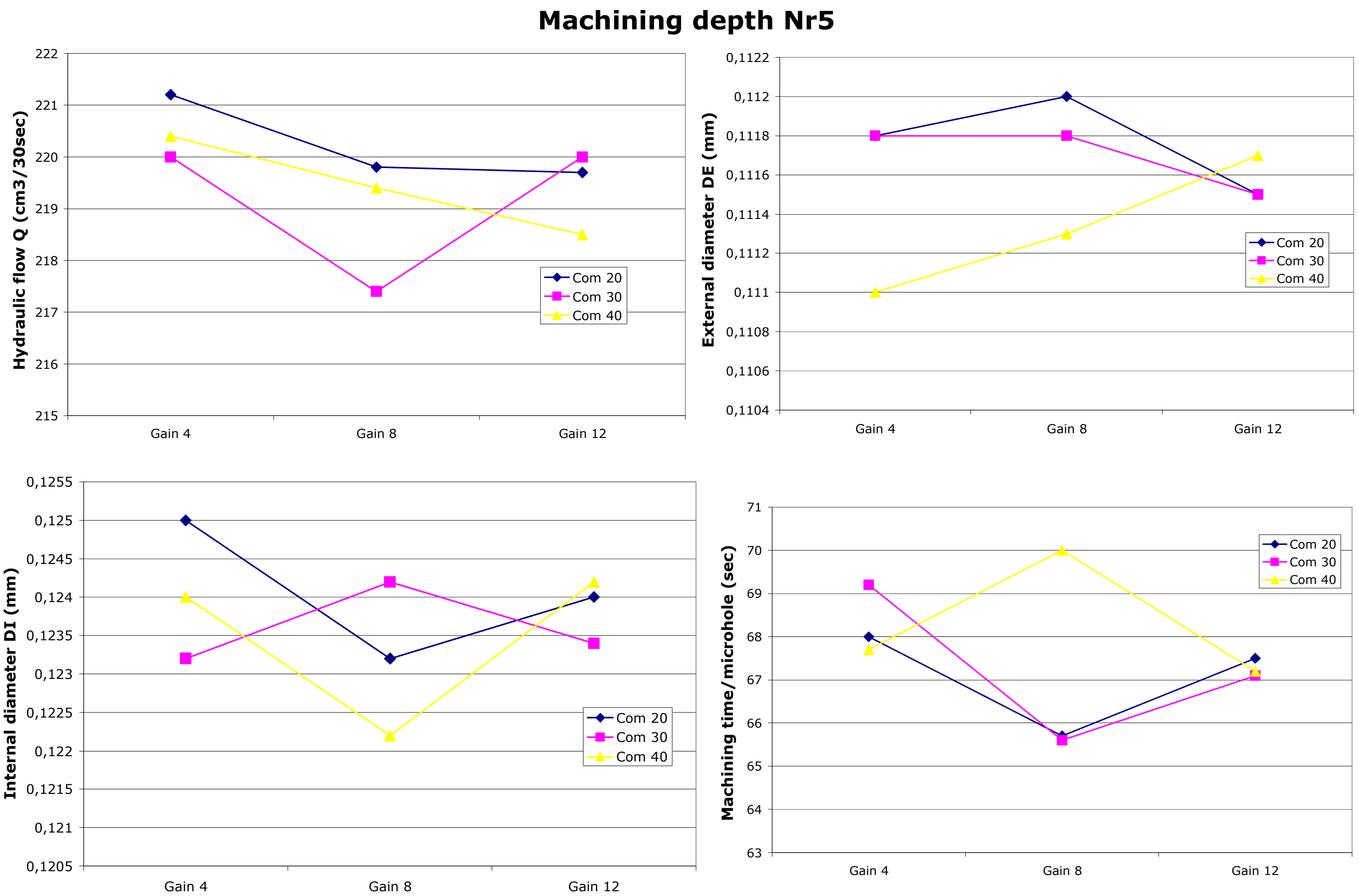

Figure 3-C: Experimental results relating to the machining depth 5

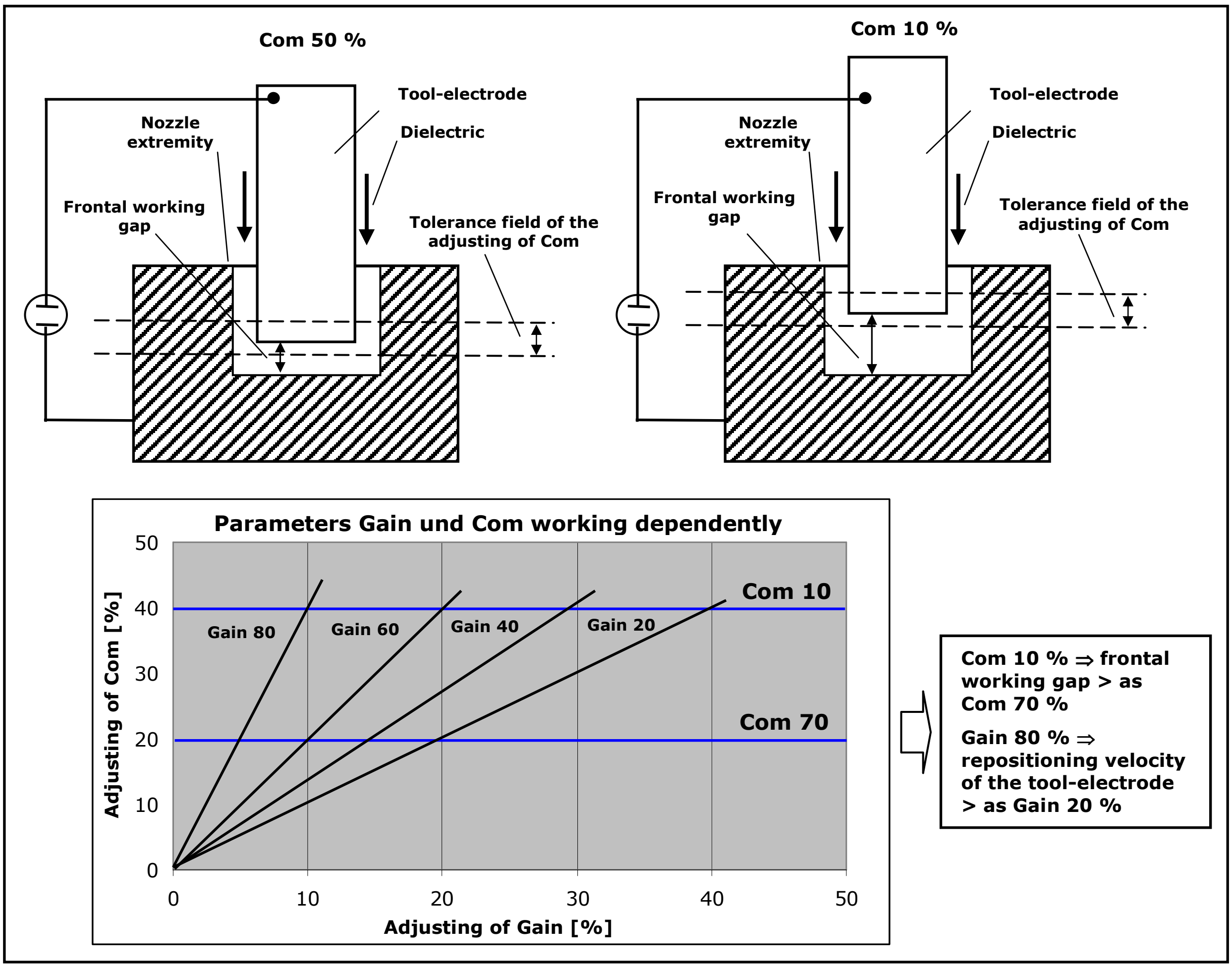

Figure 4: Operation principle of Com and Gain of the closed-loop control of the EDM-machine AGIE Quadraton I

The experimental results also indicate (practically independent on the adjustment of Com and Gain in defined levels) that there is a significant difference between the external and internal diameter of microhole (as indicated in the geometry 1 of **figure 3**). This hole conicity is a consequence mainly of the vibration level of the tool-electrode as well as of the adjusting conditions related to the parameters of the EDM-process. In some application cases the microhole conicity is totally desirable to improve the fuel injection conditions by the injection nozzles in a vehicle motor with specific characteristics of operation. Certainly the closed-loop control parameters have a great importance at the control of this special hole geometry. A highly precise control of stabilization of the EDM-machining (minimizing the formation of short circuits) and an adequation of the geometric form of hole being machined are two of the most challenges relating to an optimal adjusting of these both EDM-parameters using specific methods of DOE. A mathematical modeling of these parameters by use of regression equations (aiming to model the output-variables of the machining process) is very difficult in the practice due to their random behavior, according to the facts evidenced through the performed experiments in this research work to produce microholes for injection nozzles.

4. Conclusions

The results demonstrated in this paper firstly prove that the diameters of machined microholes can be approximately 0,04 mm greater as the diameter of the tool-electrode. The difference is certainly a direct consequence of the respective adjustment of the process parameters of the machine AGIE Quadraton I, also including the variables to be adjusted in the closed-loop control system. In this case Gain und Com have an influence not only on the internal and external diameter of the hole, but also on the machining time and hydraulic flow of the injection. For each machining depth of the EDM-process it is necessary to make an adjusting of both parameters in a combined form so that the optimal value of the output-variable being analyzed using a defined experimental planning can be achieved. The experiments showed that the hole diameter, machining time and hydraulic flow are strongly influenced through the adjustment conditions of Gain and Com, but in a totally unpredictable manner, mainly due to the fact of using a very fine tool-electrode to machine microholes in injection nozzle. This dimension of process machining is extremely sensible to the variations of the working gap conditions which are conditioned by the use of a specific adjusting of process parameters related to the electrical discharge machining. In the practice, any adjusting relating to parameters of the generator of EDM-machine also needs an adaptation of the closed-loop control parameters so that the EDM-machining process can occur in optimized way, that is, without the presence of short-circuits (that affect the desired machining stabilization) provoking irreversible distortions of the geometric quality of the machined hole.

Future analyses of the EDM-process can be concentrated in verifying the direct effects of the modification Com and Gain on the surface quality of microholes. For example, these verifications could be made using special measurement techniques to evaluate surface parameters Ra and Rz as well as to measure the level of residual thermal stresses in zones immediately below of the machined hole surface. Especially the hole roughness has a very important influence on the hydraulic characteristics of the fuel injection process of the motor, thus with consequences on the emission degree of this vehicular equipment. The total intensity of the stresses mentioned above is responsible for the fatigue resistance of the injection nozzle under influence of cyclic mechanical load of different origins during the operation of the motor.

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