

INVESTIGATION OF MATERIAL REMOVAL RATE IN ELECTRICAL DISCHARGE MACHINING (EDM) OF SMALL CYLINDRICAL SURFACES

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ABSTRACT: Electrical discharge machining (EDM) is one of the most used non-traditional machining processes. In order to detach and remove the material from the workpiece surfaces, the process uses thermoelectric energy that allows the development of electrical discharges between the workpiece and a tool electrode that are positioned in a dielectric environment. The major advantages of this machining process are reflected in its capability to cut precisely, geometrically complex material regardless hardness. Electrical discharge machining can be applied to obtain cylindrical parts from a workpiece made of an electroconductive material. The paper presents the results of an investigation concerning the effect of some machining factors on the material removal rate (MRR) in electrical discharge machining (EDM) of small cylindrical surfaces.

KEY WORDS: material removal rate (MRR), machining parameters, pulse on time, pulse off time, peak current, electrical discharge machining, small cylindrical parts.

1. INTRODUCTION

The paper deals with the investigation of the machining of small diameter cylindrical parts by electrical discharge machining. The manufacture of small diameter cylindrical parts made of hard or difficult-to-cut materials by conventional cutting processes is considered as a difficult issue, due to the need of small machining tools with adequate stiffness and the possibilities to cope with intense cutting conditions and, also, small cutting tool with the active parts made of advanced material such as CBN (cubic boron nitride) or PCBN (polycrystalline cubic boron nitride). If cold working processes are considered like an extrusion process, the main disadvantage that must be taken into consideration is its cost for machinery and upkeep.

Due to the above mentioned considerations, in some specific industrial situations the non conventional machining processes can be considered in order to machine small diameter cylindrical parts made from hard or difficult-to-cut electroconductive materials.

The nonconventional machining (or non-traditional machining) processes are considered to be the machining methods that use other forms of energy - thermal, chemical, electrical etc. instead the ones specific to the conventional machining processes, in order to remove the undesired material and obtain finally the part geometry at a proper accuracy.

The definition proposed by some researches [5] takes into considerations two essential aspects of these processes: 1. The fact that they are based on a nontraditional mechanism of interaction between the workpiece and the other elements that facilitate the

material detachment; this mechanism is called also "tool"; 2. The presence of a specific nontraditional environment that facilitates the transfer of energy between the workpiece and tool.

The electrical discharge machining (EDM) is one of the earliest and the most used from the non-traditional machining processes. In order to detach the material from the workpiece and to obtain the desired dimensions and geometry for the metallic parts, the EDM processes use the thermoelectric energy. A tool of a defined shape, called tool electrode, is electrically charged and is brought closer in proximity to the workpiece, until erosions sparks are developed. All these electrical discharges take place in a dielectric medium that is usually a liquid [1, 5, 6]. The material particles detached from the workpiece by melting and vaporizing are dissipated in the dielectric liquid and eliminated from the machining gap. The main advantages related with the use of the electrical discharge machining processes refer to the possibility of machining extremely hard or difficult-to-cut materials and to the generation of low residual stresses in the parts materials, due to the use of no physical cutting force or excess cutting tool pressure. The main limitations are related to the possibility of machining only electroconductive materials and to the low productivity, because of the slow rate of material removal.

However, by EDM machining very small parts can be obtained; generally, such parts are difficult to be machined by conventional cutting tools, because of the damages of the part surfaces caused by excess cutting tool pressure.

In order to machine small cylindrical parts distinct types of machining schemes can be used. Mircescu et al. [1] developed an analysis based on the use of ideas diagram in order to find alternatives for obtaining external cylindrical surfaces by electrical discharge machining. The analysis carried out by the authors revealed that there is the possibility to apply the electrical discharge machining on a ram electrical discharge machining and using a so-called massive tool electrode.

An analysis of the various solutions able to facilitate the obtaining of a cylindrical external surface on ram electrical discharge machines was presented by Slatineanu et al. [2]. Also, in order to test some of the theoretical considerations regarding these specific processes, some preliminary experimental researches were realized. The experiments showed the possibility to obtain thin external cylindrical surfaces by using a plate tool electrode, in which holes with various diameters were previously made.

In another scientific paper, Slatineanu et al. [3] had investigated the possibility of machining small cylindrical parts by means of tubular tool electrode. The main disadvantage reported referred to the fact that the presence in the work gap of particles detached from the electrodes could determine the generation of spurious pulses, which are able to lead to shape errors of the machined surface; in this way, conical surfaces are obtained instead of the cylindrical ones. In order to improve the machining accuracy, a machining schema based on the achieving of the work motion from up to down, to the tubular electrode placed in a vice on the machine table, had been applied. The experimental results obtained proved the diminishing of the tool electrode penetration speed in the test piece material, as the depth of the machined cavity increases.

The performance factors specific to the EDM processes are the metal removal rate, the tool wear ratio, surface finish degree, and the process cost. The main disadvantage of the electrical discharge machining is that the erosion sparks remove only a very small amount of material and because of these EDM processes are considered as high time consumption processes. For such reasons applied in the above mentioned specific processes, the material removal rate (MRR) is appreciated as an extremely important performance factor.

MRR is influenced by the physical properties of the workpiece and tool electrode materials, the machined surface dimensions and geometry, the considered machining input factors. The tool electrode materials need to have properties like high

conductiveness and/or arc erosion-resistance, in order to easily allow charge and yet resist the erosion that the EDM process determines and stimulates in the workpieces material affected by the machining process. Besides these proprieties, copper electrodes proved to be extremely efficient when smooth workpiece surface finishes are required.

Theoretically, the material removal rate in the case of electrical discharge machining processes can be determined using the following equation:

$$MRR = \frac{V}{\tau} = \frac{A_{tool\ electrode} h}{\tau} \quad [mm^3/min] \quad (1)$$

where V is the volume of material dispatched from the workpiece and for most of the die sinking EDM operations can be determined as the product between the electrode area ($A_{tool\ electrode}$) and the depth of cut (h) and τ is the machining time.

For the specific case of machining cylindrical parts by ram EDM with tubular electrodes, the volume of material dispatched from the workpiece and the material removal rate are strongly dependent on the thickness of the tool electrodes used. The volume of the material dispatched from the workpiece can be determined as:

$$V = \pi(R^2 - r^2)h = \pi h \left[(R - r)^2 + 2Rr \right] = \pi h g^2 + 2\pi h Rr \quad [mm^3] \quad (2)$$

where R is the external radius of the tubular electrode, r is the internal radius of the tubular electrode, h is the depth of cut and g is the thickness of the tubular electrode.

In the EDM processes, each machining cycle has an on-time and an off-time that are expressed in units of microseconds. The material removal rate is directly proportional to the amount of energy applied during the on-time. This energy is controlled by the peak current applied and the length of the on-time pulse. A sufficient off-time must be ensured before the start of the next cycle. Pulse off-time values strongly affect the speed and the stability of the process. If the off-time pulse is too short, the debris and vaporized material from the workpiece will not be swept away by the flow of dielectric and the fluid will not be deionized. This will cause the next spark to be unstable, causing erratic cycling and tool electrode retraction by the advancing servo.

The objective of this study is to investigate and report the effect of some specific machining conditions pulse – on time, pulse off time and peak current on the technological variable material removal rate, in the case of ram electrical discharge

machining of small cylindrical parts made of high speed steel with tubular copper tool electrodes.

2. EXPERIMENTAL SETUP

The experiments were carried out on a die-sinking EDM machine type SODICK AD3L, in the laboratory of nonconventional machining technologies from the “Gheorghe Asachi” Technical University of Iași. The test piece was made of high speed steel (containing 0.659 % C, 4.04 % Cr, 1.28 % Mo, 1.19 % V, 17.7 % W).

The machining scheme used in the study is the one presented in figure 1. Considering the appreciations made by the researchers in the previous published research papers carried out in the field of machining small cylindrical parts by using tubular electrodes, the first machining test was done by using a machining scheme in which the tubular electrode was placed in a vice on the machine table and the work motion was achieved by the workpiece that was mounted on the machine work head. Because of the relatively high machining time (62 minutes) needed in order to achieve a machining depth of approximately 10.5 mm, we abandoned this machining scheme and we used for the experimental runs a machining scheme similar to the one from figure 1. The tool electrode was mounted on the machine tool spindle. The tubular tool electrodes used have an exterior diameter of 6.5 mm and an interior diameter of 5 mm. The depth of the machined cavity was measured three times after each machining test and the average values of these measurements were considered in order to determine the machined material volume for the test runs.

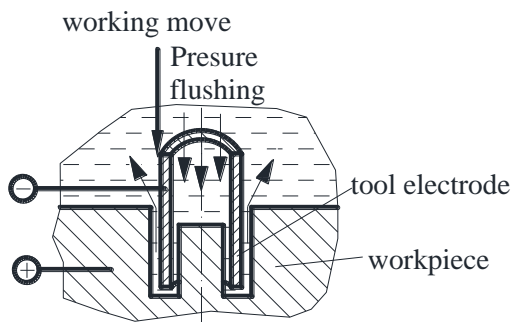


Figure 1. Machining scheme used in order to obtain small cylindrical parts by EDM

One of the main problems related to the ram electrical discharge machining processes is the unwanted discharges between the machined surfaces and the melted particles of material detached and that affect the surface integrity and part accuracy. That is why flushing the debris from the machining gap is one of the major challenges in EDM process. A solution could be flowing dielectric fluid through

the tubular electrode which is usually referred as pressure flushing. This measure is also able to improve the tool wear ratio because of its capability to cool the electrode.

Table 1. Experimental results

Exp. no.	t_p [μ s]	t_b [μ s]	I_p [A]	h [mm]	V [mm^3]	τ [sec]	MMR [mm^3/min]
1.	110	30	14	10.787	146.144	2017	0.001208
2.	85	30	14	10.597	143.563	1336	0.001791
3.	110	20	14	10.721	145.243	1890	0.001281
4.	85	20	14	10.036	135.969	1105	0.002051
5.	110	30	19	10.462	141.744	978	0.002416
6.	85	30	19	9.992	135.376	1012	0.002230
7.	110	20	19	10.608	143.712	958	0.002500
8.	85	20	19	10.457	141.676	876	0.002696

The experimental procedure chosen in order to investigate the influence of the specific machining parameters (pulse on time, pulse off time and peak current) over the material removal rate (MRR) involved the use of a full factorial plan of experiments 2^3 , by considering for each factor two levels, as one can see in table 1.

3. EXPERIMENTAL RESULTS

The obtained experimental results were processed by using specialized software. The main effect plots are presented in figure 2. The plots reflect a distinct kind of influence for the pulse on time t_p instead of the one expected, according to the theoretical considerations formulated in the first section of the present paper. As it can be seen, the peak amperage is the input parameter that influences the most the material removal rates. According to the obtained main effect plots, higher values for the material removal rates can be reached by using high peak current values.

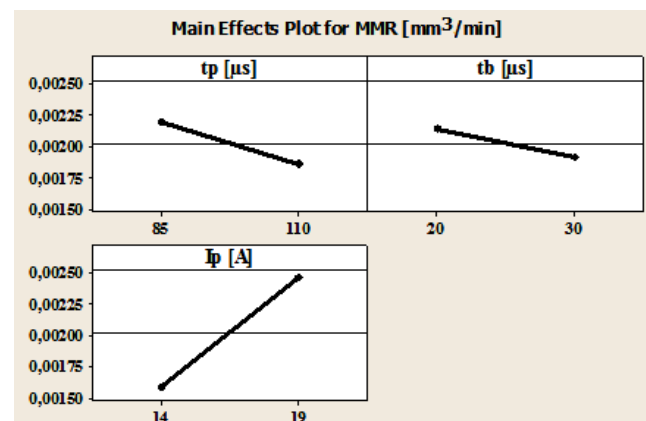


Figure 2. Main effects plots generated by the specialized software for material removal rate (MRR)

Figure 3 presents the interactions plots that result for the experimental results.

According to the data from this figure, high removal rates can be obtained if higher values for peak current in association with lower values for the pulse off time are used. As it can be seen, the level selected for the pulse on time in association with high peak current concurs to extremely appropriate values for the output parameter considered - material removal rate. By increasing the values for the input factors – pulse on time and peak current, high values of material removal rate can be obtained.

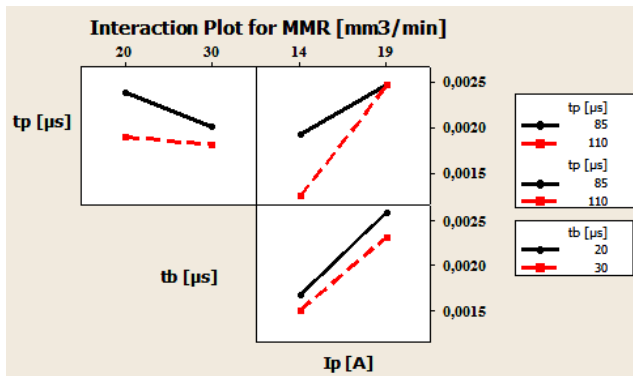


Figure 3. Interactions plots generated by the specialized software for material removal rate (*MRR*)

Regression analysis is a statistical tool for the investigation of relationships between variables and it is commonly used in order to predict the output technical characteristics.

In order to determine an efficient regression equation for the response parameter material removal rate as a function of process input parameters - pulse on time and pulse off time, nonlinear regression was used.

The empirical model obtained was a power type relation that had the following aspect:

$$MRR = 0.0029 t_p^{-0.834} t_b^{-0.252} I_p^{1.52} \quad [\text{mm}^3/\text{min}] \quad (3)$$

The empirical model highlights that the most important factor able to exert influence on the material removal rate is the peak current intensity I_p , whose exponent has the maximum absolute value, in comparison with the values of the exponents determined for the other input factors (pulse on time t_p and pulse off time t_b). The analysis of variance generated for the regression is the following:

Source	DF	SS	MS	F	P
Regression	3	0.5442	0.1814	7.10	0.044
Residual Error	4	0.1022	0.02555		
Total	7	0.64644			

The p -values for the regression is lower than 0.005, showing that we can consider the regression as significant. The residual plot presented in figure 4 also indicates a good fit. R -squared is the percentage of the response variable variation that is explained by the regression and it is used as a statistical measure of how close the data are to the fitted regression line. The value of R -squared for the empirical model given by equation (3) was of 84,2%, also showing that the model fits the experimental data obtained.

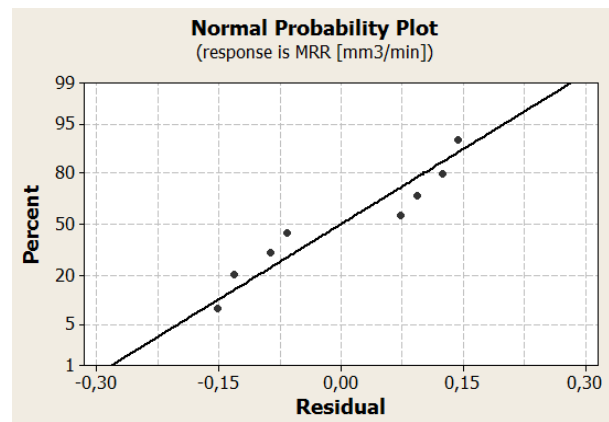


Figure 4. Normal Probability Plot obtained for material removal rate (*MRR*)

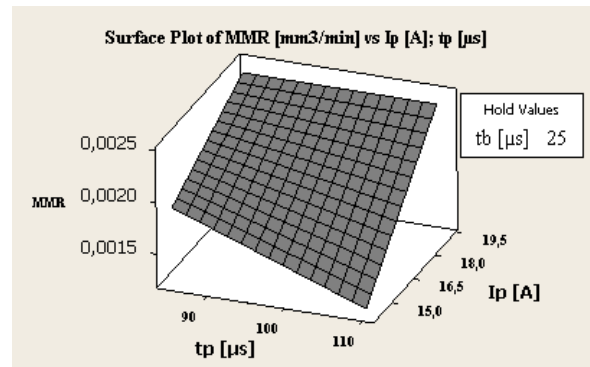


Figure 5. Influence exerted by the pulse on time t_p and peak current intensity I_p on the material removal rate *MRR* (pulse off time $t_b=25 \mu\text{s}$)

The 3D graph (figure 5) that was generated based on the empirical model (3), presenting the evolution of material removal rate parameter when changing the values of the pulse on time and peak amperage, shows that by increasing the peak current values simultaneous with the increasing of pulse on time, we can reach improved values for the *MRR* parameter.

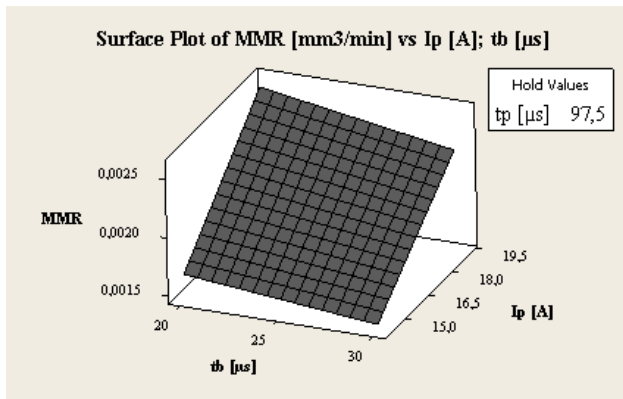


Figure 6. Influence exerted by the pulse off time t_b and peak current intensity I_p on the material removal rate MRR (pulse on time $t_p=97.5 \mu s$).

The surface plot from figure 6 shows the influence exerted by peak amperage in association with the pulse off time on the material removal rates. As it can be seen and also according to the supposition made in the first section of the paper, the MRR parameter can be increased if lower values are adopted for the pulse off time and higher for the peak current machining parameter.

4. CONCLUSIONS

The information found in the specialty literature showed that one can consider various machining methods which could be used to facilitate the generation of small external cylindrical surfaces. In the case of hard or difficult to cut materials, most of these machining methods are cost inefficient or are not able to ensure a proper surface accuracy. One of the machining methods applicable in order to machine small diameter external surfaces is the electrical discharge machining. In order to obtain small cylindrical parts by electrical discharge machining many working schemes can be adopted. For this particular experimental research, a machining scheme based on the use of ram EDM with tubular electrodes made of copper and with pressure flushing was used. The material removal rates were determined based on the geometrical calculation of the volume of material detached from the workpiece after each machining test. The paper aim was to investigate the influence of some specific machining parameters (pulse on time t_p , pulse off time t_b and peak current I_p) on the output parameter material removal rate – MRR . The experimental results were mathematical processed by means of software based on the method of least squares and a power type function empirical mathematical model was established.

The results obtained revealed that the most important factor able to exert influence on the material removal rate is the peak current intensity I_p .

Also, in order to obtain improved MRR values, the high values of the peak amperage must be associated with lower values of the pulse off time variable. The interactions plots generated and the surface plot that presents the influence exerted by the pulse on time t_p and peak current intensity I_p on the material removal rate MRR show that the interactions between the above mentioned variables (pulse current and peak current I_p) has an important role on the prediction of material removal rate parameter.

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