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A mathematical model to choose effective cutting parameters in electroerosion, EDM

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Analysis and modelling

ABSTRACT

Purpose: Machining by electroerosion is a process of removal of material by fusion, vaporization and erosion, reserved essentially for conductor and semiconductor materials. It can be used to machine metals and alloys, the tempered steels, different type of ceramic alloys, other metallic carbides and even for harder materials such as polycrystalline diamond etc. The aim of this paper is to develop a mathematical model for the effect of cutting parameters on the machining by electro discharge machining used widely in industrial applications.

Design/methodology/approach: It is about a study and detail analyzes effect of the cutting conditions in machining by electroerosion of steel 42CD4-42CrMo4 on the surface quality of the parts. The statistical method of the analysis of variance “ANOVA” makes it possible to release the considerable effects of the parameters of cut on the criteria of performance of machining by electroerosion, EDM.

Findings: The result of the study shows that the nature of the electrode used and the different grades of the materials machined by Electro Discharge Machining, EDM, influence considerably the volume of the removal of material and the surface quality of the produced parts. However, more the resistivity of the electrode increases, more relative wear of the electrode will be important and more the volume of removal of material decreases.

Research limitations/implications: This study needs more experimental results for evaluation of the cutting parameters in detail and introduce in the model developed here.

Practical implications: This model developed based on the experimental study gives very simple choice of cutting parameters depending on the materials.

Originality/value: A very simple model has been develop here after a comprehensive study and this model contains an experimental design, and application ANOVA analysis as a function of experimental results and allows to obtain a smooth surface and high quality machined pieces and can decrease at cost price of the pieces in the manufacturing engineering.

Keywords: Electroerosion; EDM; Material removal rate (MRR); Electrode wear ratio (EWR); Roughness; Mathematical modelling

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1. Introduction

Machining by electroerosion experienced a significant development during the last decades when several problems were caused following the metallographic and mechanical change of the machined surface. Several research tasks are interested in the study of optimization and the improvement of the various performances of machining by electroerosion in order to improve the productivity and the precision of machining according to the various cutting parameters. Machining by electroerosion, like any other process, presents metallurgical effects (Heat Affected Layer), it is characterized mainly, by three technical criteria: material removal, the surface quality and the relative wear of electrode - tool. The removal of material is caused mainly by a thermal phenomenon, by fusion and vaporization of metal [1].

The material flow is limited by energy concerned by each discharge and by each method itself (fusion - vaporization - ejection). It can reach 1 cm^3/min in draft machining at the beginning (energy level is around 1 J). After that, it is of a few mm^3/min in completion at the final stage (energy level is variable from 10^{-4} to 10^{-5} J). The material flow depends mainly on the intensity of the current and the duration on the impulse. It is limited by the evacuation of the eroded particles, which is often difficult. Indeed, in completion, the distance between electrodes varies from a few micrometers to hundredths of millimetre. The current of discharge has the greatest influence on the removal of material; it means that greater this current introduces more removal of materiel [2-7]. Each discharge creates a crater on the part: the micro geometrical state of surface consists of craters. Roughness can be good under the condition of discharges of weak energy: it can go down below R_a = 1 µm, and can reach 0.2 µm. Energy becomes so weak that the removal of materiel is too slow [5-6]. Puertas, Shine, Álvarez [2] have proven in their research tasks that the current of discharge to the greatest influence on the surface quality; if this current is strong, the roughness arrives an important value. They have also observed a strong reduction in roughness when the intensity of the current of discharge increases.

Whereas another study made by Puertas and Luis [6], shows that the increase in the intensity of current, “I”, allows the increase in roughness R_a up to a maximum value from which it starts to decrease. The surface quality also depends on other parameters such as the tension of starting and the nature of material of electrodes. The bibliographical analysis that has been just summarized here enabled us to define the principal parameters of the process of machining by electroerosion. The current of discharge is the parameter more influencing each performance (material flow, wear and surface quality). When the current becomes more important, the material flow becomes considerable; however, the evolution of the wear and the surface quality is different depending on the material of electrode and material of working piece. This explains the existence of an important relation between the electric parameters, material of the working piece and material of the electrode. This relation was rarely studied by the researchers in machining by electroerosion [9-13]. However, in the present study a different study was proposed for modelling the effect of the current of discharge and the material of the electrode on the material flow and the surface quality in machining by using electroerosion for steel 42CrMo4.

2. Experimental procedures

2.1. Test conditions

All the machining tests have been carried out on the electroerosion machine by penetrating “EROTECH Basic 450”, with the following parameters and test conditions:

As electrical parameters, all of the electrical parameters has been summarised in the Table 1.

Table 1.
Electrical parameters used in the present study

Discharge courant (A)	Starting tension (V)	Polarity		Impulse time (µs)	Breaking time (µs)
		Electrode	Piece		
8 à 16	120 V	Positive	Negative	8	6

As material for the working piece, a typical steel 42CD4 (42CrMo4) was used in this study and its basic characteristics were indicated in the Tables 2 and 3. This steel has a strong hardenability; it is very often used in manufacturing of the mechanical pieces: large driving shaft, crankshafts, gear pinion working without shock etc.

Table 2.
Mechanical properties of the steel 42CD4

$Re_{0.2\%}$ (MPa)	UTS (MPa)	A%	Hardness (HB)	State of heat treatment
770	980-1180	11	332	Annealing

Table 3.
Chemical composition of the steel 42CD4 (%)

C	Mn	Si	S	P	Cr	Mo	Ni	Cu	Al
0.43	0.70	0.25	0.03	0.016	0.96	0.21	0.03	0.01	0.02

Two types of materials for the electrodes were used in this study; graphite electrodes and electrolytic copper (99.9% of copper) because these are the best adapted materials to the machining of steels for obtaining a good settlement between the flow of machining and the consumption of the electrodes thanks to their mechanical and thermo physical characteristics presented in Table 4.

Table 4.
Properties of the materials of the two electrodes used

Material properties	Electrolitic copper (Cu al)	Graphite (Gr)
ρ (g/cm^3)	8.89	2.25
Hardness (HB)	70	10
Fusion Temperature (°C)	1083	3600
Boiling Temperature (°C)	2320	-
Resistivity (10^{-6} Ω.Cm)	1300	1.72
Thermal Conductivity ($W{\cdot}cm^{-1}{\cdot}°C^{-1}$)	3.9	1.25
Thermal Diffusivity ($cm^2\ s^{-1}$)	1.12	-
Dilatation ($10^{-6}{\cdot}°C^{-1}$)	16.5	3.5

A Kerosene liquid (also called paraffin oil) was used for the dielectric liquid. This liquid used during the tests has the best appropriate dielectrical properties (very low viscosity) that can facilitate very well conditions for the super finishing operations.

2.2. Strategy of the study

This work is interested in the study of the effect of the selected cutting conditions: current of discharge and electrical resistance of the electrode, on each performance: the surface quality can be explained by the measurement of average roughness R_a and the material flow calculated according to the Equation (1)

$$Volumeofmaterial = \frac{Volumeofmaterialremovedfrompiece}{Machiningtime} \quad (1)$$

The method used for this study is the method of the experimental designs; the selected plan is the factorial designs complete 2^2. Table 5 presents the matrix of the levels and the conditions of machining used in this study

The influence of the cutting parameters on the performances was studied using well known statistical method "ANOVA" and the determination of a mathematical model for facilitating the choice of the parameters has been evaluated by the "Taguchi" method [2,8].

Table 5.
Levels of matrix

Parameters		Min (-1)	Max (+1)
Electrical resistivity of the electrode (ρ_e)	A ($\mu\Omega$ cm)	1.72	1300
Current of discharge "I"	B (A)	8	16

3. Results and discussion

3.1. Study of the effect of the machining parameters on the material flow

As each test was carried out twice, the average of the two responses was used for each test. From these results, one can calculate the mean effects and total of each parameter and their interaction which enable us to determine table ANOVA (Table 6). In this table, d_f shows Degree of freedom and SS indicates Sums of the square ones

$$MS = \frac{SS}{d_f} \quad (2)$$

$$F_{test} = \frac{MS_{treatment}}{MS_{error}} \quad (3)$$

$F_{theoretical} = Fdf_{treatment}df_{error} = F_4.1 = 7.71$, that determined starting from the table of "Fisher - Snedecor" for α = 5%.

Table 6.
ANOVA table of material volume for the steel 42CD4

Source of variation	d_f	SS	MS	F_{test}		$F_{theoretic}$
A	1	59.033	59.033	1338.149	>	7.71
B	1	19.440	19.440	440.672	>	7.71
AB	1	9.932	9.932	225.146	>	7.71
Error	4	0.176	0.044			
Total	7	88.583				

The table "ANOVA" and the test of Fisher show that at a significant level of 5%, $F_{calculated}$ for A, B and AB are higher than $F_{theoretical}$, thus the null assumption can be thrown out and it can be concluded that the current of discharge "I" or "B", the electrical resistance ρ_e or A and their interaction AB, should influence significantly on the volume of the material MRR.

F_{test} for the parameter A is much higher than that of B which is very high regarding to AB, from where A is the most significant parameter, B is a significant parameter but less than A, whereas AB is the least significant parameter.

The effects of the parameters on the volume of the material MRR and those of interaction can be explained graphically by the curves of effect as indicated in Fig. 1 and Fig. 2.

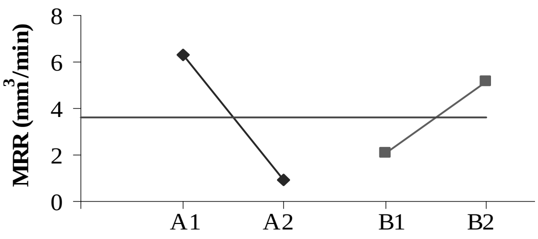

Fig. 1. Curve of effect of the volume of the material MRR

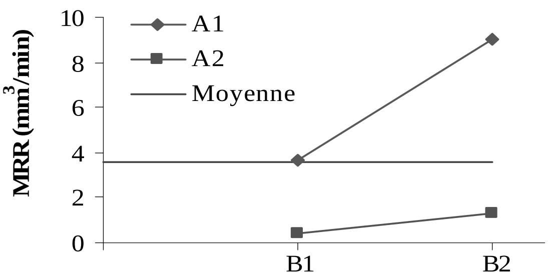

Fig. 2. Curve of effect of the interaction for the parameters

Conversely with the current of discharge "I" or "B", the electrical resistivity ρ_e or A can influence negatively the volume of the material MRR (mean effect E_A<0). However, to lead to a weak volume of material in completion, it is advised to use a material for electrode with high resistivity (low electrical conductivity) and a weaker current "I".

3.2. Study of the effect of the machining parameters on the surface quality R_a

The calculation of the average effects as well as the total average enable us to determine the table ANOVA (Table 7) of average roughness R_a after machining by electroerosion of steel 42CD4.

Table 7.
ANOVA table of mean roughness for the steel 42CD4

Source of variation	d_f	SS	MS	F_{test}		$F_{theoretic}$
A	1	16.82	16.82	100.778	>	7.71
B	1	2	2	11.983	>	7.71
AB	1	0.145	0.145	0.873	<	7.71
Error	4	0.667	0.166			
Total	7	19.6334				

As F_{test} (A) and F_{test} (B) are higher than $F_{theoretical}$ =7.71, then the parameters A and B are significant parameters contrary to their interaction AB, which does not influence significantly the surface quality (Table 7). The two curves of effect represented in Fig. 3 show well that two parameters "I" and "ρ_e" have negative effect on the average roughness R_a.

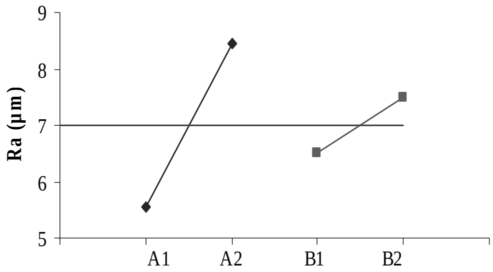

Fig. 3. Curve of effect of Ra

Indeed, roughness R_a increases by 2.9 µm by changing the electrode from electrolytic copper (ρ_e = 1.72 µΩ.cm) by the electrode from graphite (ρ_e=1300 µΩ.cm). As R_a increase only 1µm by amplifying the current of 8A. It means that the electrical resistance ρ_e influences R_a more than the current of discharge "I". The interaction of the two parameters is not significant any more because only the two lines of the curve of interaction are approximately parallel (Fig. 4).

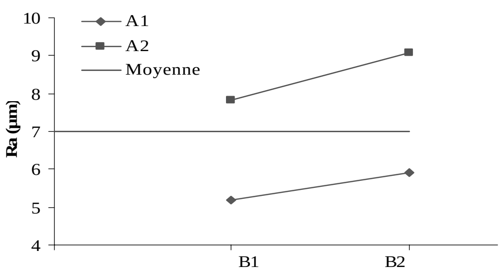

Fig. 4. Curve of interaction of R_a

3.3. Experimental - modeling

It should be noted here that to determine the mathematical models, only parameters A and B have been taken into account and neglected their interaction AB, since it is either non significant or an negligible effect regarding to A and B.

By using the napierian logarithm of the natural factors and the results of the tests, allows us to determine a mathematical model according to the linear model of the Equation (4), and according to the Taguchi method.

$$Y = b_0 + \sum b_i X_i \tag{4}$$

where: Y is the answer of the study; b_0, b_i are the coefficients of the model; X_i shows cutting parameters. Table 8 represents the matrix of the levels used for modeling.
x_0 medium of the level

$$x_0 = \frac{Max_{Level} + Min_{Level}}{2} \tag{5}$$

Δx interval of variation

$$\Delta x = \frac{Max_{Level} - Min_{Level}}{2} \tag{6}$$

$$x_i = \frac{x_i - x_o}{\Delta x} \tag{7}$$

Where x_i is the coded factor

$$x_1 = 0{,}30175947 x_1 - 1{,}16365149 \tag{8}$$

$$x_2 = 2{,}885390082 x_2 - 7 \tag{9}$$

In case where only three coefficients are important, the response can be written as follow:

$$\ln Y = b_0 + b_1 X_1 + b_2 X_2 \tag{10}$$

Thus, one can substitute X_i by their value as a function of x_i. After the treatment these equation, the model is written in the final form as follow:

$$Y = \alpha A^a B^b \tag{11}$$

Table 8.
Levels of matrix

	Natural Factors			
	General Model		Linear Model	
Factors	ρ_e (µΩ.cm)	I (A)	x_1=Ln (ρ_e)	x_2=Ln (I)
Level -	1.72	8	0.54232429	2.079441542
Level +	1300	16	7.17011954	2.772588722
x_0	-	-	3.85622192	2.426015132
Δx	-	-	3.31389763	0.34657359

3.4. Determination of the mathematical model for the material flow

The mathematical model of the material flow (MRR) is written by the Equation 12.

$$MRR = 0,20210978 \rho_e^{-0,303265556} I^{1,4462104} \quad (12)$$

The model determined by the Equation 12, can provide the results very close to the practical applications. In fact, the gap between $MRR_{experimental}$ and $MRR_{theoretical}$ are very weak as shown in Table 9 and Fig. 5.

Table 9.
Residue of the volume of material MRR

Test	$MRR_{experimental}$	$MRR_{theoretical}$	Residue
1	3.647	3.469	0.1775
2	0.442	0.464	-0.0226
3	8.993	9.453	-0.4602
4	1.332	1.267	0.0448

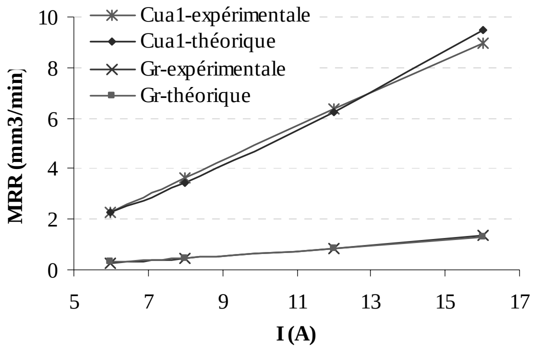

Fig. 5. Evolution of volume of material MRR as a function of the current of discharge

This weak residue is also observed by the comparison of the two curves obtained calculated and experimentally for the flow of materials according to the two factors.

It seems that they are very close, similar and so that they were overlapped (Fig. 5). The determined model of MRR is validated and will be a means facilitating the choice of the parameters of cutting. After the study of the variation as a function of the current of discharge "I", for two different material electrodes, electrolytic copper (ρ_e = 1.72 μΩ.cm) and graphite (ρ_e = 1300 μΩ.cm), It can be noted that the material MRR flow increases by amplifying the current of discharge from 8 to 16 Amps. In fact, for a given time and a constant voltage discharge, if current "I" is amplified, the energy of discharge increases. This facilitates the fusion and the vaporization of material of the part from where higher materials flow.

Additionally, the nature of the electrode influences the material flow; indeed, electrolytic copper provides a flow higher than that obtained by the graphite electrode. During the machining of steel 42CD4-42CrMo4, the material flow reaches 9 mm^3/min with a copper electrode and 1.8 mm^3/min with a graphite electrode for I = 16 Amps: copper gives the best material flow. It means that if the resistivity is important, the material MRR flow is low. From the mathematical model, one can deduce the equation from the current of discharge as a function of the material flow and also from the resistivity of material of electrode (as given in the Equation 13).

$$I = 3,021065764 MRR^{0,691462302} \rho_e^{0,2096967} \quad (13)$$

3.5. Determination of a mathematical model for average roughness

A second study on the effect of the parameters of machining by electroerosion on the surface quality was carried out. The R_a east mathematical model defines by the Equation (14).

$$R_a = 3,260 \rho_e^{0,063} I^{0,203} \quad (14)$$

Fig. 6 shows that for the steel "42CD4-42CrMo4", the curve of variation of the average roughness calculated as a function of the current of discharge for two materials of electrode (electrolytic copper (Cu-al) and graphite (gr.)) is very close to the curve of experimental roughness. In fact, the gap between R_a experimental and R_a theoretical are very weak (Table 10), the residue varies between 0.01 and 0.3.

Table 10.
Average roughness during the machining of "42CD4-42CrMo4

Test	$R_{a\ experimental}$	$R_{a\ theoretical}$	Residue
1	5.18	5.155	0.024
2	7.81	7.846	-0.036
3	5.91	5.937	-0.027
4	9.08	9.037	0.042

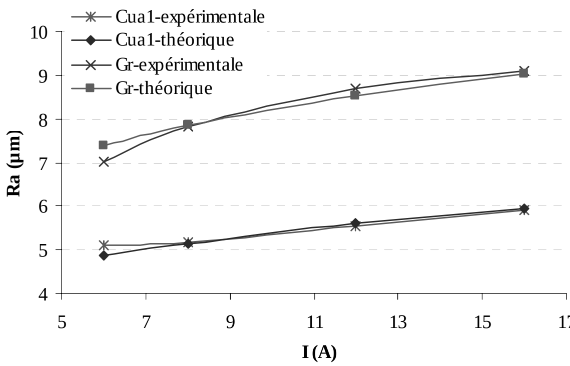

Fig. 6. Evolution of R_a on the machined surface (experimental et calculated) as a function of the current of discharge

4. Conclusions

Some following conclusions are drawn from the experimental study:

Evaluation of the experimental results carried out during machining by electroerosion of steel “42CD4-42CrMo4” show that only the electrical parameters and the nature of the electrode used influence considerably the results of the process:

- Volume of removal material, MRR flow, and the surface quality R_a, increase for a varying current of discharge from 8 to 16 Amps.
- The use of an electrolytic copper electrode (ρ_e = 1.72 μΩ·cm) generates a higher material flow than that of machining with the graphite electrode with the same conditions of machining.
- Average roughness is lower in the case of the use the electrolytic copper electrode. Thus the modelling of the various criteria of performance, material MRR flow and surface quality R_a, would be an important estimating tool of the results according to the cutting conditions.

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