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Section

Mecanical Engineering

Experimental modeling of EDM process using the experimental design method
Modélisation expérimentale du processus EDM par la méthode des plans d'expériences

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Abstract

One of the non-traditional machining processes is the electrical discharge machining "EDM". It remains a widely used process in the manufacture of dies and molds. In this process, the material removal is occurred by a series of succeeding and non-stationary electrical discharges between the electrode and the work piece. These discharges are separated from each other in time. Machining parameters such as the pulse time "Ton", the rest time "Toff", the discharge current "I" and the electrical resistivity of the electrode material "Rho" have a major influence on the piece and the tool during machining. The material removal rate plays a very important role in the manufacturing domain as it decides on the time and ultimately the final cost. In this work we studied the interaction between these parameters and their effects on the material removal rate "MRR" then on the relative tool wear "Wr". The modeling through statistical methods using the method design of experiments showed concordance between the experimental results and those calculated.

Résumé

L'un des processus d'usinage non-traditionnels est l'usinage par électroérosion "EDM" c'est un procédé très utilisé dans la fabrication des matrices et des moules. L'enlèvement de matière se produit par une série de décharges électriques non-stationnaires successives, séparées les unes des autres dans le temps. Les paramètres d'usinage tels que le temps d'impulsion "Ton", le temps de repos "Toff", le courant de décharge "I" et la résistivité électrique du matériau de l'électrode "Rho" ont une influence majeure sur la pièce et l'outil lors de l'usinage. Le taux d'enlèvement de matière joue un rôle très important dans le domaine de la fabrication, car il détermine le temps et le coût final. Dans ce travail, nous avons étudié l'interaction entre ces paramètres et leurs effets sur le taux d'enlèvement de matière "MRR", puis sur l'usure relative de l'outil "Wr". La modélisation par des méthodes statistique en utilisant les plans d'expériences a montré une concordance entre les résultats expérimentaux et ceux calculés.

Key Words / Mots-clés

Current/ Courant de décharge ; MRR/ Débit de matière enlevée ; Pulse time/ Temps d'impulsion ; Rest time/ Temps de repos ; Wr/ Usure relative de l'outil

Content

Abreviations

Grandeur		Unité	
Symbole	Désignation	Nom	Symbole
Ton	Pulse time	Microseconds	µs
Toff	Rest time	Microseconds	µs
I	Discharge current	Ampere	A
MRR	Material removal rate	Centimeter cube / minute	cm^3/min
Rho	Electrical resistivity	Ohm-meters	10^{-8} Ωm
Wr	Relative tool wear	Percentage	%
EDM	Electrical discharge machining		
ANOVA	Analysis of variance		
DOF	Degree of freedom		
SS	Sum of squares		
MS	Mean square		
R2	The multiple linear correlation coefficient		

1. Introduction

Electrical discharge machining is a material removal machining process. It is characterized in that the material removal is obtained by a non-stationary succession of electric discharges, separated from each other in time **[1]**.

We can see the theoretical trend of a series of discharges developed in a given time (in microseconds) in Figure 1. The choice of machining parameters such as pulse time "Ton", rest time "Toff", the discharge current intensity "I" and the material of the used electrode have a direct influence on the material removal rate "MRR" defined as the volume of material removed from the machined piece per time unit. These parameters have also a direct influence on the relative wear "Wr" defined as the volume of material removed from the electrode by the volume of material removed from the machined piece **[2]**.

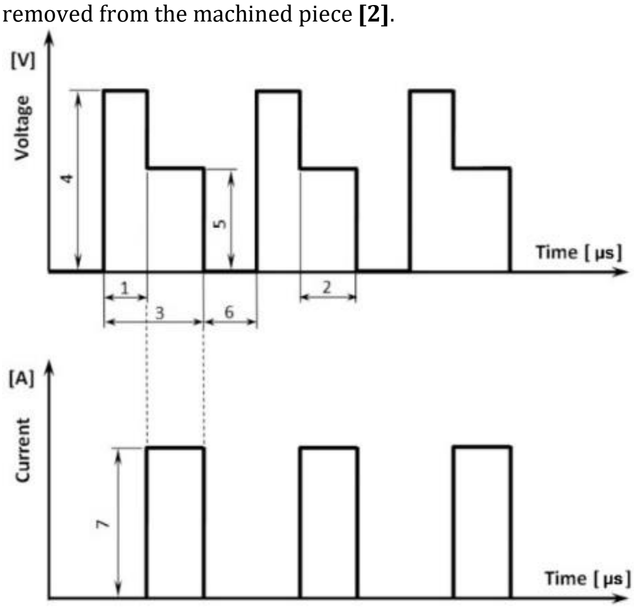

Fig. 1. Schematic representation of pulses

Where:

1-Charging time
2-Discharge time
3-Pulse time "Ton"
4-Charging voltage
5-Discharge voltage
6- Rest time "Toff"
7- Discharge current "I"

These parameters represent the main parameters of the electrical discharge machining and are chosen according to the desired machining result.

In order to correctly choose the most influential parameters in this process and to appropriately adopt the low level and the high level of each parameter, some experimental studies have been developed during the last years. Kapil Banker et al. **[3]** Optimized machining parameters of EDM with experiments following the Taguchi method "L9 table". The parameters considered are the discharge current (10-14 A), Ton (5-7 µs) and Toff (7- 9 µs) using a copper electrode and an AISI 304 Steel as a work piece, with three levels for each parameter. The Ton parameter has the greatest effect on the MRR. The optimum parameters to maximize MRR are I=14 A, Ton=7 µs, Toff=8 µs.

The experimental results achieved during EDM machining of 42CD4 steel realized by A. Medfai et al. **[4]** have proven that only two parameters affect the material removal rate "MRR", which are the discharge current 'I" and the electrode material. The material removal rate increases for a varying discharge current from 8 to 16 A. The use of an electrolytic copper electrode generates a higher material removal rate than that generated in machining with a graphite electrode at the same machining conditions.

A. Torres and al. **[2]** have machined Inconel alloy 718 with an electrolytic copper electrode by varying four parameters: discharge current "I", pulse time "Ton", duty cycle "η" and open-circuit voltage "U". They have studied the influence of these parameters on the surface roughness, the electrode wear and the material removal rate. They showed that the pulse time has a great deal of influence to the electrode wear.

F. Klocke and al. **[5]** studied the influences of different graphite grades on the performance of graphite electrodes in sinking EDM. They used the Böhler steel W300 as work-piece material, and used as parameters: the discharge current "I" and the pulse duration "T". They chose five different kinds of graphite with significantly different physical characteristics concerning their specific electric resistance, thermal conductivity and grain size. The performance of each grade was evaluated in terms of material removal rate and tool wear for roughing. They showed that the discharge current has the main influence on the material removal rate and the discharge duration has main influence on the tool wear and there is no direct link between the performance and the grain size regarding MRR and Wr. The influence on the tool wear was not as obvious but seems to be a combination of the grain size and electric resistance at least according to the limited number of material properties which were investigated.

Vikas et al. **[6]** carried out the optimization of the MRR for "EN41" material based on the four input parameters like the pulse time "Ton", rest time "Toff", discharge current (8-24 A) and gap voltage (40-80 V). He found out that the current along with the pulse-off time had a larger impact over the MRR followed by some of the interaction plot, while the effect of the other parameters were negligible.

S. Vineet et al. **[7]** machined higher speed steel "M2 HSS" with a cooled copper electrode and used as parameters the discharge current (3-7 A), the pulse time (100-500 µs), the duty cycle and voltage GAP (50-70 V). They found that discharge current I, pulse time Ton and duty cycle influence significantly the material removal rate, MRR increases with the increase in discharge current. This could be due to an increase in discharge energy with increase in discharge current, which improves the rate of melting and evaporation. They found that the MRR decreases with the increase in pulse time initially but after a certain value of pulse time 200 µs, it increases (200-500 µs). They found that even the duty cycle influence MRR, the increase of duty cycle effectively means the application of the discharge for a longer duration and this causes an increase in MRR.

Sameh S. Habib **[8]** machined a conductive metal matrix composite Al/SiC using copper electrodes (99.7% Cu, 0.12% Zn, 0.02% Pb, 0.02% Sn) with positive polarity. She developed a comprehensive mathematical model for correlating the interactive and higher order influences of various electrical discharge machining parameters through response surface methodology, utilizing relevant experimental data as obtained through experimentation. The analysis of the experimental observations highlights that the electrode wear ratio in electrical discharge machining is greatly influenced by the various process parameters, the electrode wear ratio increases with an increase of both pulse on time and peak current and decreases with increase of both of SiC percentage and gap voltage.

Similarly, T. Muthuramalingam et al. **[9]** also carried out the improvement of the MRR on the different input parameters by varying four parameters, the electrode material (copper, brass, and tungsten carbide), the GAP voltage, the discharge current and DF duty factor with different levels of treatment (Taguchi L27 orthogonal table). They showed that the electric conductivity of the electrode material has no influence on the EDM machining characteristics. The optimum parameters values are: Gap voltage of 70V, discharge current of 15A and the DF duty factor of 0.6 with a copper electrode gave the better response characteristics. The confirmation test proved that the obtained optimal combinations meet the requirements involved in the EDM process.

C.J. Luis and al. **[10]** machined a conductive ceramic such as siliconised silicon carbide (SiSiC) with an electrolytic copper electrode by varying five design factors: discharge current "I", pulse time "Ton", duty cycle "η", open-circuit voltage "U" and dielectric flushing pressure "P" with three levels of treatment and only for the finish stages. Second-order models were selected to carry out this study for both response variables material removal rate and electrode wear. They showed that discharge current I, pulse time Ton and flushing pressure P (in descending order of importance) influence the electrode wear for a confidence level of 95%, and it was verified that an increase in the flushing pressure (within the considered work interval 20 - 60 kPa) will cause a decrease in the electrode wear.

In this work, we propose an experimental study followed by modeling the material removal rate "MRR" and the relative electrode wear "Wr" depending to four parameters "Ton", "Toff", "I" and "Rho".

2. Materials and experiences

2.1. Study strategy

In this work, we are interested to study the effect of four EDM machining parameters: the pulse time "Ton", rest time "Toff", the discharge current "I" and the electrical resistivity of the electrode "Rho" on the material removal rate MRR and the electrode relative wear Wr. The cutting parameters are selected in two levels for each parameter as shown in Table 1.

Table. 1 Levels matrix

Parameters	Level 1	Level 2
Ton (µs)	7	10
Toff (µs)	6	8
I (A)	32	64
Electrical resistivity : Rho (10^{-8} Ωm)	1300 (Graphite)	1,72 (Copper)

We used the design of experiments method **[11]**. The selected plan is the full factorial 2^4 =16 tests (Table 2).

Table. 2 design of experiments

Experiment N°	Parameters			
	Ton (µs)	**Toff** (µs)	**I** (A)	**Rho** (10^{-8}Ωm)
1	7	6	32	1300
2	10	6	32	1300
3	7	8	32	1300
4	10	8	32	1300
5	7	6	64	1300
6	10	6	64	1300
7	7	8	64	1300
8	10	8	64	1300
9	7	6	32	1,72
10	10	6	32	1,72
11	7	8	32	1,72
12	10	8	32	1,72
13	7	6	64	1,72
14	10	6	64	1,72
15	7	8	64	1,72
16	10	8	64	1,72

The influences of machining parameters on the material removal rate MRR and the relative wear Wr of the electrode was studied based on the statistical method: analysis of variance "ANOVA" **[12]**.

2. 2. Test conditions

The tests were performed on the EDM machine "EROTECH basic 450" Figure 2 with the following technological parameters summarized in Table 3.

Fig. 2. The EDM machine (EROTECH basic 450)

Table. 3 Technological parameters of tests

The primary technological parameters	Ton	7 – 10
	Toff	6 – 8
	I	32 - 64
The secondary technological parameters	PLS	1
	GAP	8
	PRT	6
	TUP	200
	TPW	1800
	SRV	7
	TUR	7
	V	2
	AUX	8
Polarity	Electrode	Positive
	Piece	Negative

Where:

Ton: Pulse Time
Toff: Rest time
I: Discharge current
PLS : To select the optimal evacuation signal
GAP : Gap between electrode and piece (µm)
PRT : Allows adjustment of the sensitivity of the pollution protection
TUP : Up time of the electrode, to avoid pollution (ms)
TPW : Down time, working time (ms)
SRV : Allows the adjustment of the sensitivity of the electrode feed control system
V : The charging voltage (V)
AUX : auxiliary protection, allows the setting of the sensitivity of the shorting protection in the GAP

Two types of electrode materials were used in this study. Electrodes in electrolytic copper "ETP" and graphite electrodes "EDM-AF5". The physical characteristics of these two materials are shown in Table 4.

Table. 4 The material properties of two electrodes used

Characteristics	Copper	Graphite
Density (g/cm^3)	8,89	2,25
Temp. melting (°C)	1083	3600
Hardness HB	70	10
Electrical resistivity (10^{-8} Ωm)	1,72	1300

The tests was conducted using C45 steel parts. This steel is very frequently used in the manufacture of press tools and forging. Table 5 and Table 6 respectively provide the mechanical properties and the chemical composition of C45 steel.

Table. 5 Mechanical properties of steel C45

Rm (N/mm^2)	Re (N/mm^2)	A %	Hardness HB	Density (g/cm^3)
560 / 620	275 / 340	14 / 16	170	7,85

The C 45 steel is an unalloyed steel having a level of 0.5 to 0.52% carbon “C”.
In addition to carbon “C” the chemical elements present in steel can be classified into three categories as shown in Table 6.
The impurities, originally present in the blast furnace ingredients used to produce the iron that will be used to make the steel, are the sulfur “S” and the phosphorus “P” present in the coke.
The added element is manganese “Mn” in this case.
The accompanying elements that the steelmaker uses to control the various physicochemical reactions necessary to finally obtain a steel conforming to the specification. This is the case of silicon element “Si”.

Table. 6 Chemical composition of steel C45 (% of weight)

C	S	Mn	P	Si
0,52 - 0,50	≤ 0,035	0,50 - 0,80	≤ 0,035	0,40 maxi

The dielectric liquid used in the tests is kerosene “ELECTRA 100”. It has the properties suitable for this type of machining.
The machined depth was kept constant for each test and the machining time was measured in real time using a digital stopwatch with a precision of ± 1ms.
The masses of parts and electrodes was measured before and after processing with a digital scale with a precision of ± 0,01g.

3. Results and discussion

3.1. Effects and Interactions of machining parameters

Since the mass of the piece and electrode was measured before and after machining, the material removal rate “MRR” was then calculated as follows and an example calculation in Table 7 **[13]**:

$$MRR = \frac{(\text{Initial weight piece} - \text{Final weight piece})}{\text{Processing time} \times \text{piece density}} * 60 \qquad (1)$$

Table. 7 An example calculation for MRR measurement in test 1

First test		Second test	
Initial weight piece (g)	1063.18	Initial weight piece (g)	1058.89
Final weight piece (g)	1058.89	Final weight piece (g)	1055.9
Processing time (s)	423	Processing time(s)	312
Density piece ($g\ cm^{-3}$)	7.85	Density piece ($g\ cm^{-3}$)	7.85
MRR (cm^3/min)	0.077517	MRR (cm^3/min)	0.073248
The average of the two measures of MRR (cm^3/min)		0,075382	

The relative wear “Wr” is then calculated as follows and an example calculation in Table 8 :

$$Wr = \frac{(\text{Initial weight electrode} - \text{Final weight electrode})}{(\text{Initial weight piece} - \text{Final weight piece})} * 100 \qquad (2)$$

Table. 8 An example calculation for Wr measurement in test 1

First test		Second test	
Initial weight electrode (g)	95,210	Initial weight electrode (g)	92,840
Final weight elect. (g)	95,209	Final weight elect. (g)	92,839
Initial weight piece (g)	1063.18	Initial weight piece(g)	1058,89
Final weight piece (g)	1058.89	Final weight piece (g)	1055,90
Wr (%)	0,02331	Wr (%)	0,033445
The average of the two measures of Wr (%)		0,0283774	

To calculate the MRR and Wr, the mass of the part and electrode was measured before and after machining in gram, the measurement of the machining time was in seconds (Table 7 and 8). It is noted that all the tests was repeated twice. All the results of the MRR and Wr are shown in Table 9.

Table. 9 Experimental results of MRR and Wr

Test N°	**Results : MRR** (cm^3/min)			**Results : Wr** (%)		
	Reading 1	Reading 2	Mean	Reading 1	Reading 2	Mean
1	0,07751	0,07324	0,07538	0,0233	0,0334	0,0283
2	0,08676	0,09870	0,09273	3,2312	5,7522	4,4917
3	0,05268	0,05815	0,05541	3,2200	2,3411	2,7805
4	0,18801	0,08824	0,13812	2,3809	5,1470	3,7640
5	0,12972	0,10155	0,11564	2,3885	0,0000	1,1942
6	0,21838	0,21078	0,21458	2,8571	2,6168	2,7369
7	0,09186	0,09287	0,09237	2,7463	1,9455	2,3459
8	0,18409	0,18934	0,18672	3,5587	3,2110	3,3848
9	0,08768	0,08557	0,08663	14,973	15,099	15,036
10	0,08838	0,09059	0,08948	0,0157	1,3182	0,6669
11	0,04680	0,03946	0,04313	14,401	19,367	16,884
12	0,05798	0,08365	0,07082	0,0269	0,0148	0,0209
13	0,14152	0,14847	0,14499	25,527	20,347	22,937
14	0,19926	0,19945	0,19936	0,9803	0,1312	0,5558
15	0,09311	0,09082	0,09197	27,815	28,301	28,058
16	0,17018	0,15019	0,16019	0,0080	0,0093	0,0087

From these results, we were able to prepare and study the effects and interactions of machining parameters.

3.1.1. The effects and interactions of machining parameters on the material removal rate

The treatment of the results shows the average effects of machining parameters on the material removal rate.

Table. 10 Average effects on MRR

Level	Ton	Toff	I	Rho
1	0,0881945	0,127352833	0,081467808	0,12137259
2	0,144003568	0,104845235	0,150730261	0,110825478
Effect	-0,02790453	0,01125379	-0,03463122	0,005273556
Delta	0,055809068	0,022507598	0,069262453	0,010547112
Rank	2	3	1	4

Table 10 gives the MRR average in the level 1 and the level 2 for each parameter and the effect of each parameter.
Delta represents the difference between level 2 and level 1.
Rank classes the parameters in descending order effects.

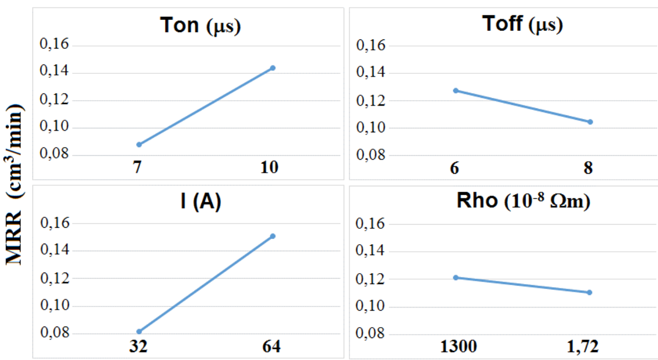

Fig.3. Representation of average effects on MRR

The graph of the average effects of Figure 3 shows that the material removal rate “MRR” is unduly influenced by the discharge current “I” and the pulse time “Ton”. While the influence of the rest time “Toff” is reversed and less significant. We can also see that the use of a copper or graphite electrode has a very low influence on the material removal rate.

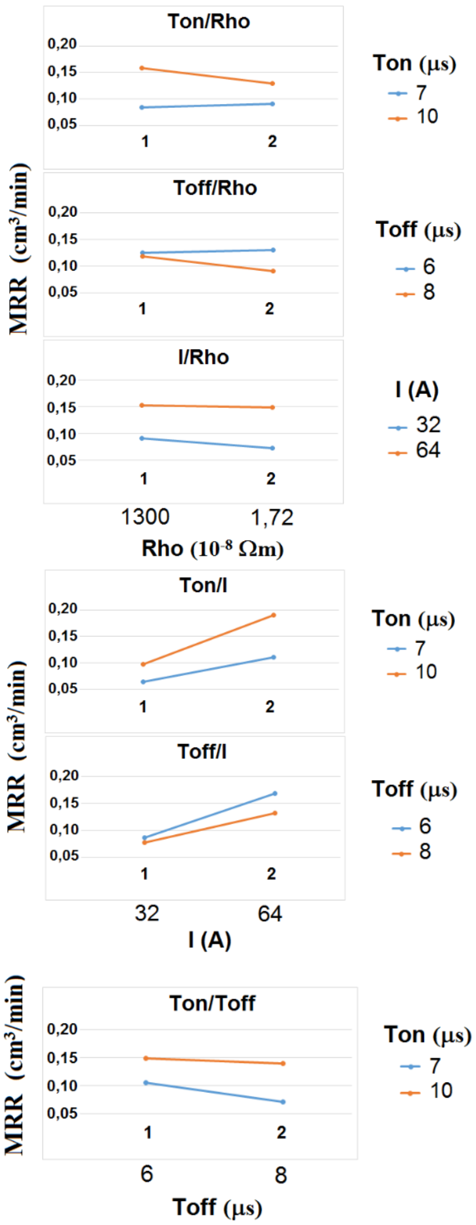

Fig. 4. Interactions graphics of parameters on MRR

The interaction graphics on Figure 4 are not parallels; we deduce that there is mutual interactions between the various parameters. Thus, a pulse time "Ton" more important, for example, increases the effect of the discharge current "I". There is a strong interaction between "Ton-I", "Toff-Rho" and "Ton-Rho". However, there is a weak interaction between the discharge current "I" and the electrode material "Rho".

3.1.2. Study of the effects and interactions of machining parameters on the relative wear of the electrode Wr

The treatment of the results shows the average effects of machining parameters on the relative wear of the tool "Wr".

Table 11: average effects on Wr

Level	Ton	Toff	I	Rho
1	11,15833629	5,956037868	5,459216153	2,590847663
2	1,953755818	7,156054241	7,652875955	10,52124445
Effect	-4,6022902	0,60000819	1,0968299	3,96519839
Delta	9,20458047	1,2000164	2,1936598	7,9303968
Rank	1	4	3	2

Table 11 gives the relative wear average in level 1 and level 2 for each parameter and the effect. Delta represents the difference between level 2 and level 1 and Rank the class in descending order effects.

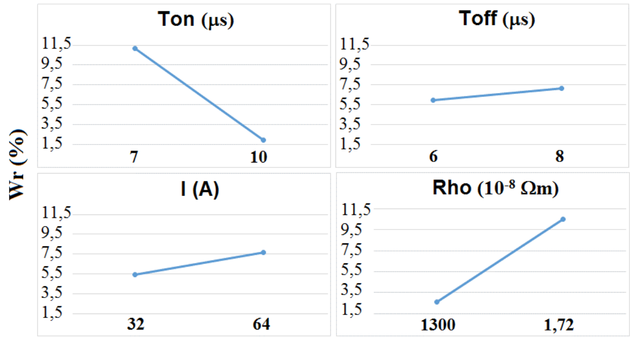

Fig. 5 Graphs of average effects on Wr %

The graph of the average effects of Figure 5 shows that the electrode relative wear "Wr" is highly influenced by the pulse time "Ton" and electrode material "Rho". While the influences of the discharge current "I" and the rest time "Toff" are less significant. The relative tool wear "Wr" is low with a graphite electrode but is high with a copper electrode.

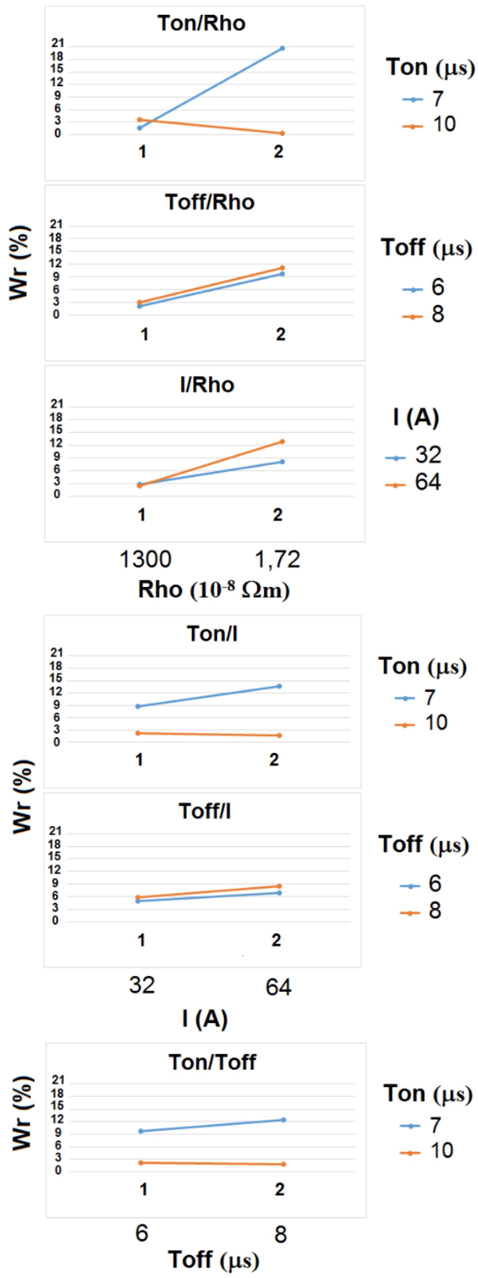

Fig. 6 Graphs of interactions on Wr %

In the graphics of interaction Figure 6 there is no interaction between the discharge current "I" and the rest time "Toff" but a weak interaction between the electrode material "Rho" and the rest time "Toff". However, the lines of the other graphs of interactions are not parallels, we deduce that there is mutual interactions between the various parameters.

3.2. Modeling MRR and Wr according to the machining parameters

The simplest model taking into account only the first order interactions may be determined as follows (3):

$$Y = b0 + b1 * X1 + b2 * X2 + b3 * X3 + b4 * X4 + b12\,(X1 * X2) + b13\,(X1 * X3) + b14\,(X1 * X4) + b23\,(X2 * X3) + b24\,(X2 * X4) + b34\,(X3 * X4) + b123(X1 * X2 * X3) + b124(X1 * X2 * X4) + b134(X1 * X3 * X4) + b234(X2 * X3 * X4) + b1234\,(X1 * X2 * X3 * X4) \quad (3)$$

With:
X1 = Ton ; X2 = Toff ; X3 = I ; X4 = Rho
The complete classical experiment plan makes it possible to estimate the 15 unknown parameters of the model that are:

- bi: the effects of order 1 factors
- bij: the effects of 2 interactions
- bijk: the effects of 3 interactions
- bijkl: the effects of 4 interactions
- b0: the average.

3.2.1. Modeling MRR according to the machining parameters

We begin by modeling the MRR using the simplest possible model taking into account only the factors and interactions of the first order. In other words, we try to explain at best the average response using the following model (4):

$$MRR = b0 + b1 * Ton + b2 * Toff + b3 * I + b4 * Rho + b12(Ton * Toff) + b13(Ton * I) + b23(Toff * I) + b14(Ton * Rho) + b24(Toff * Rho) + b34(I * Rho) + b123(Ton * Toff * I) + b124(Ton * Toff * Rho) + b134(Ton * I * Rho) + b234(Toff * I * Rho) + b1234(Ton * Toff * I * Rho) \quad (4)$$

Statistical analysis of this model brings us to the analysis of variance "ANOVA" table 12 as follows.

Table. 12 Analysis of variance MRR

Source of Variation	SS	DOF	MS	F Ratio	Signif
Regression	0.0817	15	0.0054	14.2904	< 0.01 ***
Residues	0.0061	16	0.0004		
Total	0.0878	31			
***Significant at 99,9 % confidence level F0.001(15,16)=5,27< 14.2904					

$$SS_T = SS_R + SS_E \quad (5)$$

$$MS_R = \frac{SS_R}{DOF_R} \quad (6)$$

$$MS_E = \frac{SS_E}{DOF_E} \quad (7)$$

The F-ratio value calculate:

$$F\ Ratio = \frac{MS_R}{MS_E} \quad (8)$$

With:
T: Total
E: Residue
R: Regression
Confidence level:

- To 95 % confidence level when $F0.5(DOF_R, DOF_E)$ < F-ratio value calculate
- To 99 % confidence level when $F0.01(DOF_R, DOF_E)$ < F-ratio value calculate
- To 99,9 % confidence level when $F0.001(DOF_R, DOF_E)$ < F-ratio value calculate

$F0.5\ (DOF_R, DOF_E)$, $F0.01\ (DOF_R, DOF_E)$ and $F0.001\ (DOF_R, DOF_E)$ are determined by Fisher statistic table.
This shows that the model used is adjusted since as the sum of squares due to residues (0.0061) is then less than the sixteenth of the sum of squares due to regression (0.0817).
The probability that the variance due to the regression will be significantly different from the residues.
The model can be found excellent quality, since there is 99.9% chance that it actually explains the measured variations in the response. In other words, variations in the experimental response are not considered random since the ANOVA precisely shown to be significantly higher in the experimental scatter significant at 99,9 % confidence.

Table. 13 Study statistics coefficients of MRR

Standard Deviation of the response	0.019526289
R2	0.931
R2A	0.865
Number of degrees of freedom	16

The multiple linear correlation coefficient R2

$$R2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T} \quad (9)$$

With 0 ≤ R2 ≤ 1, the fitted model is more "close" the observed responses R2 is near to 1.
This is confirmed by more detailed analysis further given in Table 13, the multiple linear correlation coefficient quantifies now clearly the high quality of fit since
R2 = 0,931 ≈ 1.

Table. 14 Estimates and statistics of factors MRR

Name	Coeff.	F.Inflation	Standard Deviation	t.exp.	Sigf. %
b0	0.116099028		0.003451793	33.63	< 0.01 ***
b1	0.027904528	1.00	0.003451793	8.08	< 0.01 ***
b2	-0.011253797	1.00	0.003451793	-3.26	0.491 **
b3	0.034631228	1.00	0.003451793	10.03	< 0.01 ***
b4	-0.005273559	1.00	0.003451793	-1.53	14.6
b12	0.006215766	1.00	0.003451793	1.80	9.1
b13	0.011578853	1.00	0.003451793	3.35	0.403 **
b23	-0.006662022	1.00	0.003451793	-1.93	7.2
b14	-0.008764134	1.00	0.003451793	-2.54	2.19 *
b24	-0.008040809	1.00	0.003451793	-2.33	3.33 *
b34	0.003674591	1.00	0.003451793	1.06	30.3
b123	-0.005057484	1.00	0.003451793	-1.47	16.2
b124	-0.001380422	1.00	0.003451793	-0.40	69.5
b134	-0.000073934	1.00	0.003451793	-0.02	98.3
b234	0.002908041	1.00	0.003451793	0.84	41.2
b1234	0.003686178	1.00	0.003451793	1.07	30.1

For each coefficient of bi or bij, it is possible to test the hypothesis of its nullity
The hypothesis to test the meaning of each coefficient is:
H0: bi = 0
If the hypothesis H0: bi = 0 is not rejected, this indicates that the parameter can be eliminated from the model.
The statistical test for this hypothesis is the Student's test [12] which leads us to calculate a "ti".

$$ti = \frac{\text{Coeff of } bi}{\text{standard deviation of bi}} \quad (10)$$

Table 14 shows the estimated values of the MRR model factors. From these results, we note that the effect of the discharge current I (b3 = 0,03463) and the discharge time Ton (b1 = 0,0279) were statistically most significant, while the effect of the rest time Toff is negative (b2 = -0,011254). Hypothesis H0 is not rejected for parameter b4, this indicates that this parameter can be removed from the model.
The interaction parameters b12, b23, b34, b123, b124, b134, b234 and b1234 of this model are not significants. It is interesting to note that only the interaction effect between factors (1-3) (1-4) and (2-4) appears to be significantly different from zero.

We find this same result by considering the graph of the effects of each factors and the effects of the interactions figure 3 and 4.

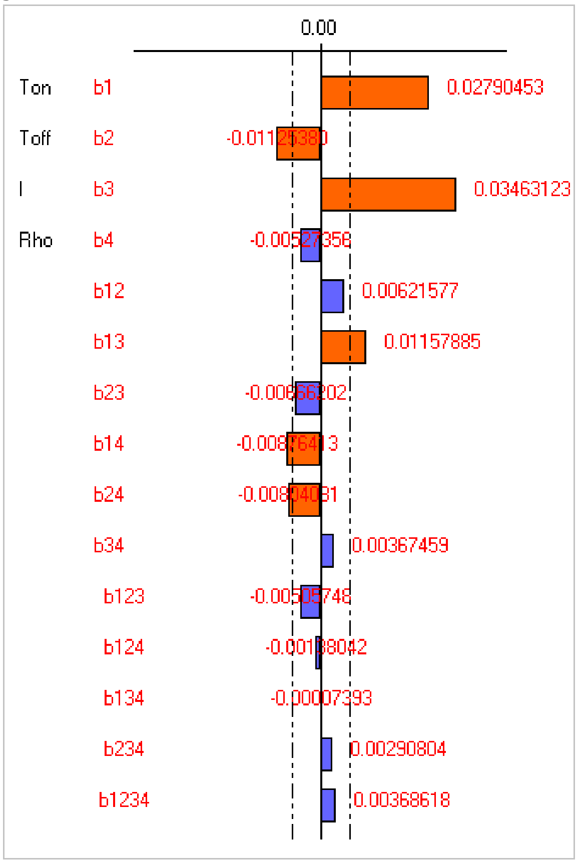

Fig.7 Graphic effect settings on the material removal rate

In addition, regarding the interaction effects, it is clear that the interaction between the pulse time Ton and the discharge current I (b13 = 0, 011578853), the interaction between the pulse time Ton and the electrical resistivity of the electrode material Rho (b14 = -0, 008764134) and the interaction between the rest time Toff and the electrical resistivity of the electrode material Rho (b24=-0,008040809) appear to be significantly influential. Other interactions are very weak.

Following these results, we considered only the effects of three parameters: Ton, Toff and I and three interactions "I-Ton", "Ton-Rho" and "Toff-Rho". This was in agreement with the results of careful examination of the effects graphs in Figure 3 and interactions Figure 4.

The expression of the MRR model given by equation (4) becomes:

$$MRR = 0.1161 + 0.0279 \times Ton - 0.0112538 \times Toff + 0.0346312 \times I + 0.011578\ (Ton \times I) - 0.0087641\ (Ton \times Rho) - 0.00804\ (Toff \times Rho) \qquad (11)$$

Table 15 residues of MRR, shows that the difference between the values experimentally measured and those calculated by the proposed model is low less than 0.049 which confirms that our fit is very good.

Table. 15 Table of residues MRR

N°Exp	MRR Yexp.	MRR Ycalc.	Difference
1	0.0775173	0.07538285	0.00213445
2	0.0732484	0.07538285	-0.00213445
3	0.0867619	0.0927349	-0.005973
4	0.0987079	0.0927349	0.005973
5	0.0526832	0.0554173	-0.0027341
6	0.0581514	0.0554173	0.0027341
7	0.1880155	0.13812875	0.04988675
8	0.088242	0.13812875	-0.04988675
9	0.1297297	0.11564335	0.01408635
10	0.101557	0.11564335	-0.01408635
11	0.2183803	0.2145812	0.0037991
12	0.2107821	0.2145812	-0.0037991
13	0.0918682	0.0923722	-0.000504
14	0.0928762	0.0923722	0.000504
15	0.1840946	0.18672015	-0.00262555
16	0.1893457	0.18672015	0.00262555
17	0.0876871	0.08663145	0.00105565
18	0.0855758	0.08663145	-0.00105565
19	0.0883845	0.0894891	-0.0011046
20	0.0905937	0.0894891	0.0011046
21	0.0468094	0.0431369	0.0036725
22	0.0394644	0.0431369	-0.0036725
23	0.0579891	0.07082115	-0.01283205
24	0.0836532	0.07082115	0.01283205
25	0.1415207	0.1449986	-0.0034779
26	0.1484765	0.1449986	0.0034779
27	0.1992633	0.19936115	-0.00009785
28	0.199459	0.19936115	0.00009785
29	0.0931181	0.09197335	0.00114475
30	0.0908286	0.09197335	-0.00114475
31	0.1701874	0.16019205	0.00999535
32	0.1501967	0.16019205	-0.00999535

The comparison between curves MRR experimental (measured responses) and MRR calculate in Figure 8 (responses predicted by the model) shows the small difference and confirms the fit is very good.

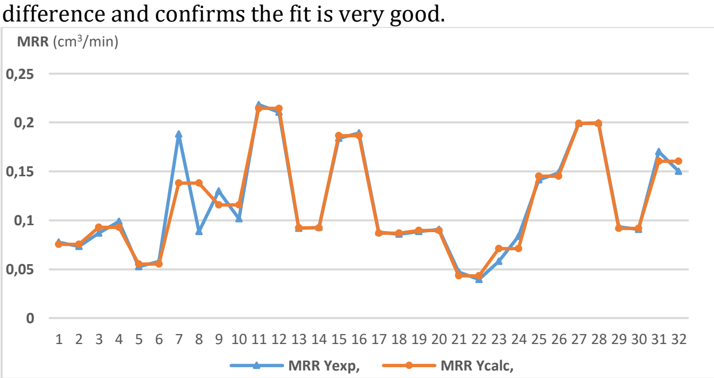

Fig.8. Curves of MRR exp. and MRR calc.

Figure 8 also shows a good agreement between the model predictions and experimental verifications.

3.2.2. Modeling the relative wear of the electrode (Wr) based on machining parameters

Wr is modeled again using a model of the same form as RRM taking into account only the factors and interactions of the first-order using the following model (12):

$$Wr = b0 + b1 * Ton + b2 * Toff + b3 * I + b4 * Rho + b12(Ton * Toff) + b13(Ton * I) + b23(Toff * I) + b14(Ton * Rho) + b24(Toff * Rho) + b34(I * Rho) + b123(Ton * Toff * I) + b124(Ton * Toff * Rho) + b134(Ton * I * Rho) + b234(Toff * I * Rho) + b1234(Ton * Toff * I * Rho) \qquad (12)$$

Statistical analysis of this model brings us to the analysis of variance "ANOVA". Table 16 shows that the model used is adjusted since the sum of squares due to residues (37,7317) is then less of the sum of squares due to regression (2411,23) and shows three stars to the significance of the regression for a confidence level of 99, 9 %.

Table 16: analysis of variance Wr

Source of variation	SS	DOF	MS	F Ratio	Signif
Régression	2411.23	15	160.749	68.1651	< 0.01 ***
Résidus	37.7317	16	2.35823		
Total	2448.97	31			

***Significant at 99,9 % confidence level F0.001(15,16)=5,27< 68.1651

As seen in Table 17, the linear correlation coefficient R2 = 0,985≈1. The model can be judged excellent quality **[12]**.

Table 17: study statistics coefficients of Wr

Standard Deviation of the response	1.535652669
R2	0.985
R2A	0.970
Number of degrees of freedom	16

Table 18: estimates and statistics of factors Wr

Name	Coeff.	F.Inflation	Standard Deviation	t.exp.	Signif. %
b0	6.556046056		0.271467604	24.15	< 0.01 ***
b1	-4.602290231	1.00	0.271467604	-16.95	< 0.01 ***
b2	0.600008188	1.00	0.271467604	2.21	4.20 *
b3	1.096829906	1.00	0.271467604	4.04	0.0948 ***
b4	3.965198394	1.00	0.271467604	14.61	< 0.01 ***
b12	-0.7591382	1.00	0.271467604	-2.80	1.29 *
b13	-1.378991831	1.00	0.271467604	-5.08	0.011 ***
b23	0.196695475	1.00	0.271467604	0.72	47.9
b14	-5.605843756	1.00	0.271467604	-20.65	< 0.01 ***
b24	0.122005525	1.00	0.271467604	0.45	65.9
b34	1.272162719	1.00	0.271467604	4.69	0.0248 ***
b123	-0.012369337	1.00	0.271467604	-0.05	96.4
b124	-0.261169175	1.00	0.271467604	-0.96	35.0
b134	-1.020846806	1.00	0.271467604	-3.76	0.171 **
b234	0.224808362	1.00	0.271467604	0.83	42.0
b1234	-0.384389287	1.00	0.271467604	-1.42	17.6

Now regarding to the estimation of various unknown model parameters, we find that the effect of pulse time "Ton", the discharge current "I" and the resistivity of the electrode "Rho" are statistically significant for a confidence level of 99, 9 %. The effect of the rest time "Toff" is lower a confidence level of 95 %.

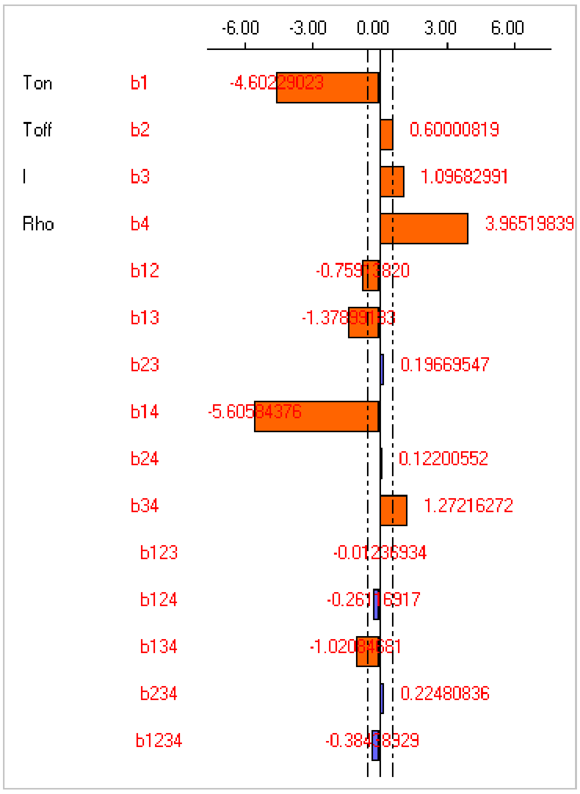

Fig.9 Graphic study of the different coefficients of Wr

When accessing the results of the statistical analysis (Table 18) and graphical study (Figure 9) of the different coefficients of the proposed model, we note that only the effect of the pulse time "Ton", the discharge current "I" and the resistivity of the electrode material "Rho" are statistically significant (b1=-4.60229023; b3=1.0968299; b4=3.96519839), while effect of the rest time "Toff" is lower (b2 = 0.60000818). For interactions, it is clear that only the effects of interactions between "Ton-Rho", "Ton-I" and "I-Rho"are significantly influential (b14 = -5.60584375; b13= -1.37899183; b34=1.27216271) for a confidence level of 99,9 % and the interaction between "Ton-I-Rho" is influential (b134 = -1.0208468) for a confidence level of 99%. While the interaction between the pulse time "Ton" and rest time "Toff" is lower (b12 = -0.7591382). Other interactions are very weak.

So we will consider the effects of factors "Ton", "Toff", "I" and "Rho" in addition to interactions "Ton-Rho", "Ton, I", "I-Rho", "Ton-I-Rho" and "Ton-Toff" to develop the empirical model of relative wear.

The expression of the Wr model given by equation (12) becomes:

$$Wr = 6.556 - 4.6 \times Ton + 0.6 \times Toff + 1.09683 \times I + 3.965 \times Rho - 0.76\,(Ton \times Toff) - 1.379\,(Ton \times I) - 5.606\,(Ton \times Rho) + 1.2721\,(I \times Rho) - 1.021\,(Ton \times I \times Rho) \quad (13)$$

Table 19 shows that the difference between the experimental values and those calculated by the empirical model. This difference is very weak. This confirms that our original choice is very good.

Table 19: Table of residues Wr

N°Exp	Wr Yexp.	Wr Ycalc.	Difference
1	0.02331	0.0283774	-0.0050674
2	0.0334448	0.0283774	0.0050674
3	3.2312925	4.49175245	-1.26045995
4	5.7522124	4.49175245	1.26045995
5	3.2200358	2.78058645	0.43944935
6	2.3411371	2.78058645	-0.43944935
7	2.3809524	3.7640056	-1.3830532
8	5.1470588	3.7640056	1.3830532
9	2.388535	1.1942675	1.1942675
10	0.000000	1.1942675	-1.1942675
11	2.8571429	2.73698265	0.12016025
12	2.6168224	2.73698265	-0.12016025
13	2.7463651	2.3459452	0.4004199
14	1.9455253	2.3459452	-0.4004199
15	3.5587189	3.38486405	0.17385485
16	3.2110092	3.38486405	-0.17385485
17	14.973262	15.03648855	-0.06322655
18	15.0997151	15.03648855	0.06322655
19	0.0157233	0.66699535	-0.65127205
20	1.3182674	0.66699535	0.65127205
21	14.4016227	16.8846058	-2.4829831
22	19.3675889	16.8846058	2.4829831
23	0.0269542	0.0209176	0.0060366
24	0.014881	0.0209176	-0.0060366
25	25.5274262	22.93762615	2.58980005
26	20.3478261	22.93762615	-2.58980005
27	0.9803922	0.5558129	0.4245793
28	0.1312336	0.5558129	-0.4245793
29	27.8156997	28.05879325	-0.24309355
30	28.3018868	28.05879325	0.24309355
31	0.0080775	0.008716	-0.0006385
32	0.0093545	0.008716	0.0006385

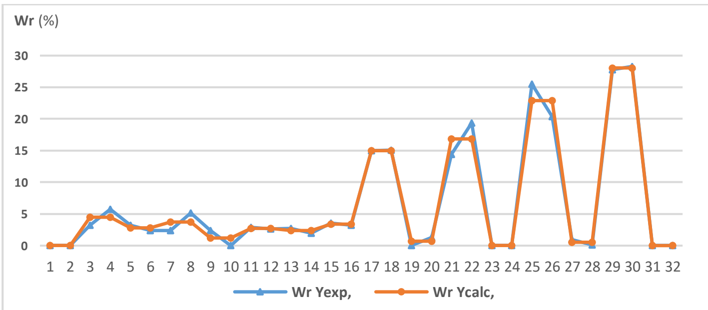

Fig.10 Comparing $Wr_{exp.}$ and $Wr_{calc.}$

Figure 10 also shows the comparison of experimental results and the values which were predicted by model. Good agreement between the model predictions and experimental verifications has been demonstrated in those wear conditions.

4. Conclusions and perspectives

The experimental study of a C45 steel work piece provided important quantitative results for an obtaining experimental modeling of the material removal rate by EDM and show that only the electrical parameters used to influence considerably the results of the process.

Material removal rate plays a very important role in the manufacturing domain as it decides on the time and ultimately cost. We studied the effects of primary

technological parameters such as pulse time “Ton”, rest time “Toff”, discharge current “I” using a copper electrode and a graphite electrode by electrical discharge machining “EDM” process to establish an experimental models that defines the rate of removal of material “MRR” and the relative wear “Wr”.
We first analyze the effects of controllable parameters of machining such as pulse time 7-10 µs, rest time 6-8 µs, the discharge current 32-64 A and the electrode material to establish an experimental model that defines the flow and the wear as a function of the machining parameters.
We used statistical methods such as design of experiments, analysis of variance.
This study has led us to the following results:
- The material removal rate “MRR” increases with the increase of the discharge current “I” and pulse time “Ton”. It has been found that the most influential factor for MRR is the current intensity. The higher the current intensity, the greater the MRR.
- A pulse time “Ton” higher increases the effect of the discharge current “I”.
- The relative wear of the electrode “Wr” decreases greatly with increasing pulse time “Ton”.
- The relative tool wear “Wr” is low with a graphite electrode but is high with a copper electrode.
It was also observed from the modeling through statistical methods using the method of design of experiments showed concordance between the experimental results and those calculated.
As perspectives, and in order to better adjust the models, work will be conducted with three levels for each parameter and use a plan of experience that can generate models of order 2.

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Références

[1] D. KREMER « Usinage par électroérosion » *Techniques de l’ingénieur : Traité Mécanique.* 2000 volume BM7 251, BM7251–1 à BM7251–22
[2] A. Torres, I. Puertas, C.J. Luis « Modelling of surface finish, electrode wear and material removal ratein electrical discharge machining of hard-to-machine alloys » *Journal of Precision Engineering.* 2015 Vol 40, pp 33–45. doi:10.1016/j.precisioneng.2014.10.001
[3] K. Banker, U. Prajapati, J. Prajapati, P. Modi « Parameter optimization of Electro Discharge Machine of AISI 304 Steel by using Taguchi Method » *International Journal of Application or Innovation in Engineering & Management.* 2014 Volume 3, Issue 8, pp 20–24
[4] A. Medfai, M. Boujelbene, E. Bayraktar « A mathematical model to choose effective cutting parameters in electroerosion EDM » *Journal of Achievements in Materials and Manufacturing Engineering.* 2011 Volume 47, Issue1 pp 97–102
[5] F. Klocke, M. Schwade, A. Klink, D. Veselovac « Analysis of material removal rate and electrode wear in sinking EDM roughing strategies using different graphite grades ». *Journal of Procedia*. 2013 CIRP 6, pp163–167 doi:10.1016/j.procir.2013.03.079
[6] Vikas, A. K. Roy, K. Kumar « Effect and Optimization of Machine Process Parameters on Material Removal Rate in EDM for EN41 Material Using Taguchi » *Journal of Procedia Materials Science.* 2014 Vol 6, pp 383–390 doi.org/10.1016/j.mspro.2014.07.049
[7] V. Srivastava, Pulak M. Pandey « Statistical Modeling and Material Removal Mechanism of Electrical Discharge Machining Process with Cryogenically Cooled Electrode » *Journal of Procedia Materials Science.* 2014 Volume 5, pp 2004–2013. doi.org/10.1016/j.mspro.2014.07.533
[8] Sameh S. Habib « Study of the parameters in electrical discharge machining through response surface methodology approach » *Journal of Applied Mathematical Modelling.* 2009 Vol 33, pp4397–4407. doi:10.1016/j.apm.2009.03.021
[9] T. Muthuramalingam, B. Mohan « Application of Taguchi-grey multi responses optimization on process parametrers in electro erosion » *Journal of Measurement.* 2014 Volume 58, pp 495–502. doi.org/10.1016/j.measurement.2014.09.029
[10] C.J. Luis, I. Puertas, G. Villa « Material removal rate and electrode wear study on the EDM of silicon carbide » *Journal of Materials Processing Technology.* 2005 Vol 164–165, pp889–896. doi:10.1016/j.jmatprotec.2005.02.045
[11] J. Goupy « Factorial experimental design: Detecting an outlier with the dynamic variable and the Daniel’s diagram » *Chemometrics and Intelligent Laboratory Systems.* 2006 vol 80, pp 156–166
[12] Walter Tinsson « Plans d'expérience : constructions et analyses statistiques » *Springer Berlin Heidelberg.* 2010, ISBN 978-3-642-11472-4
[13] S. Raj, K. Kumar « Optimization of MRR and overcut in die sinking electro-discharge machining of EN45 material using Grey-Taguchi technique » *International Journal of Applied Engineering Research*. 2015 Volume 10, No 55 pp 3652–3656