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Mathematical Modeling of Machining Parameters in Electrical Discharge Machining of FW4 Welded Steel

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Abstract**—**FW4 is a newly developed hot die material widely used in Forging Dies manufacturing. The right selection of the machining conditions is one of the most important aspects to take into consideration in the Electrical Discharge Machining (EDM) of FW4. In this paper an attempt has been made to develop mathematical models for relating the Material Removal Rate (MRR), Tool Wear Ratio (TWR) and surface roughness (R_a) to machining parameters (current, pulse-on time and voltage). Furthermore, a study was carried out to analyze the effects of machining parameters in respect of listed technological characteristics. The results of analysis of variance (ANOVA) indicate that the proposed mathematical models, can adequately describe the performance within the limits of the factors being studied.

Keywords**—**Electrical Discharge Machining (EDM), linear regression technique, Response Surface Methodology (RSM)

I. NTRODUCTION

FW4 is a welded steel, that is the most important and applicable welded material on the basis of chromium. Using welded materials increases the lifetime of forging moulds by more than 150% and periodical replacement time of moulds up to 200% as compared to moulds made of ordinary steel tool. Also it causes a decrease in materials and mould's expenses to 62%. The hardness of weld metal will be controlled in the scale of 30-50 HRC, and the weld metal will be resistant in hot strength, high temperature, wear and thermal fatigue crack [1]. At present, EDM is a widespread technique used in industry for high-precision machining of all types of conductive materials such as: metals, metallic alloys, graphite, or even some ceramic materials, of any hardness [2].

EDM is a non-traditional machining process based on removing material from part by means of successive electrical discharges occurring between an electrode and a workpiece immersed in a dielectric fluid [2]. Since EDM is a complex machining process, in order to achieve the economic objective of this process, optimal cutting conditions have to be

determined and so mathematical models need to be established.; Therefore, Statistical-mathematical models are always used by scientists to describe the correlation between characteristics and machining output results, and setting or input parameters. The Fuzzy Theory, Artificial Neural Network and Regression Analysis are the most important and major modeling methods, employed in the EDM process modeling [3]. Regression analysis is regarded as a powerful tool for representing the relation between input parameters and process responses [3, 4].

Puertas et al. presented mathematical models for electric discharge machining of WC-Co, SiC and conductive ceramics on the basis of experiment designing techniques. They introduced the obtained mathematical models, using regression analysis [5-8]. Khoshkish et al. studied the effects of electrode tool materials and machining input parameters (such as: current, pulse-on time) on AISI D3 EDM characteristic, by the use of variance analysis and experiments designing techniques. They reported that the graphite electrode, having highest material removal rate and precise dimension and low tool wear ratio, is the most appropriate material for steel machining [9]. George et al. used regression models and plotted response surfaces for some carbon-carbon composite and concluded that the most important input parameter, affecting the EDM process characteristic, is the spark current [10].

In this paper, the relation between input parameters of EDM process such as peak current, pulse-on time and voltage and the process outputs have been modeled, using the techniques of Design of Experiments (DOE) method, multi linear regression techniques and response surface methodology (RSM). Also the effect of input parameters on the characteristic of machining FW4 steel has been analyzed. The result of this research, leads to desirable process outputs (MRR, TWR and R_a) and economical industrial machining, by optimizing the input parameters.

II. TESTING PROCEDURE

A. Experimental apparatus

Experiments were performed on a CNC Die-Sinking ED machine of type CHARMILLES ROBOFORM200 equipped with an iso-pulse generator. The tool and workpiece mass change were measured by using a digital balance (CP224S-Surtorius) with readability of 0.1mgr. The surface roughness parameter R_a was measured by using surface roughness measuring instrument (Mahr- Perthomether M2). An Electronic circuit is designed and made to control the process, monitoring of input parameters and printing EDM pulses. The ammeter has been connected in series with the spark gap so that all sparking current flows through it to measure average current. The voltmeter has been connected across the gap between the tool and workpiece to measure average voltage.

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These two equipment besides the arc and short circuit stability LEDs as well as tool position reading serve as a tool for stability monitoring. The oscilloscope (Hitachi VC-6524) of storage type has been employed to capture and hold random frames of gap voltage variations against time, which then will be transferred and stored on the PC hard disk through a serial cable and port connection.

B. Materials

The material used for workpiece was FW4 welded tool steel. To prepare FW4 samples, first a sheet of common steel was used as a base, and the welding process was done using a Forgeweld semi-automatic MIG welding station. Welding process occurs by the systematic deposition of weld layers achieving a build-up of 3-5mm per layer with "covered welding wires of FW4", in several pulses. Separating welding dost from the basic sheet, raw blocks of Fw4 steel are prepared. Raw blocks were cut to circular tablets 20mm height by wire EDM and then ground to parallel faces. EC-16 graphite tool electrode material has a particle size from 3 to 5 micron. Graphite tools were cut from 20mm dia. Rod and machined by using a very accurate CNC lathe. Table I shows the samples and tools physical and mechanical properties [11].

TABLE I
WORK PIECE AND TOOL ELECTRODES PHYSICAL PROPERTIES

Properties of FW4 (Work piece)		Properties of EC-16 (Tool)	
Density	7.7623 (×1000 kg/m³)	Bulk Density	1.811 (g/cm³)
Melting point	2670 (˚C)	Specific Resistance	1650 (μohm-cm)
Poisson's Ratio	0.34	Flexural Strength	750 (kg/cm²)
Elastic Modulus	210 (GPa)	Shore Hardness	70
Hradness	45.5 HRC		
Thermal Conductivity	27.2 (W/m.K)		

III. DESIGN OF EXPERIMENTS

In the present section, the design factors and response variables selected for this work, as well as the methodology employed for the experimentation, will be described.

A. Design factors selected

There are a large number of factors to consider within the EDM process, but in this work peak current (I), pulse- on time (Ton) and voltage (V) have only been taken into account as design factors. The reason why these three factors have been selected as design factors is that they are the most widespread and used amongst EDM researchers.

B. Response variables selected

The response variables selected for this study refer to the speed of the EDM process, i.e., Material Removal Rate (MRR), and the efficiency of the graphite electrode used, i.e., Tool Wear Ratio (TWR). These response variables are defined in Eqs. (1) and (2), respectively:

$$MRR = \frac{VMR_p}{T} \quad (1)$$

$$\%TWR = \frac{VMR_E}{VMR_p} \times 100 \quad (2)$$

Where MRR is the material removal rate (mm³/min), VMR_P is the difference of the sample volume in mm³, before and after the machining process (g), VMR_E is the tool lost volume (mm³), during the machining process and T is the machining time (min).

C. Fractional factorial design employed

Experiments were designed on the basis of the experimental design technique that has been proposed by Box and Hunter [12]. The design finally chosen was a 2^{3-1} fractional factorial one with three central points. The addition of three central points allows us to carry out lack-of-fit tests for the first-order models proposed, where a total of 8 experiments for these first-order designs were made. In case the first-order model turned out not to be adequate for modeling the behavior of the response variable to be studied, this was widened by adding 6 star points, thus giving a central composite design with the star points located in the centers of the faces. Thus, the case of the second order model consisted of a total of 17 experiments, i.e., the previous 8 of the first-order model plus the new 3 of the star points. A summary of the levels selected for the factors to be studied is shown in Table II. Table IV shows the design matrix for the second-order models as well as the values obtained in the experiments for the response variables studied in this work, i.e., MRR, TWR and R_a. As can be observed in this table, rows 1–8 correspond to the fractional factorial design, rows 9–11 correspond to the central points and finally, the star points are placed in the six last rows of the design matrix.

TABLE II
FACTORS AND LEVELS SELECTED FOR THE EXPERIMENTS

Factors	Levels		
	-1	0	+1
Current (A)	8	16	24
Pulse-on time (μs)	12.8	25	50
Voltage (v)	120	160	200

TABLE III
EXPERIMENTAL CONDITIONS AND PROCESS VARIABLES

Condition and variables	Description
Generator type	Iso pulse (ROBOFORM 200)
Work piece	FW4 Welded Steel Ø20×20 mm
Tool	Graphite Ec-16 Ø18×20mm
Tool polarity	Positive
Dielectric	Oil Flux ELF2
Flashing type	Normal submerged
Depth of cut(mm)	2.0
GAP(mm)	0.09
Power available(A)	8,16,24
Pulse durations (μs)	12.8,25,50
Voltage(v)	120,160,200
Reference voltage(v)	70
Duration of interval between two pulses (μs)	6.4
Machining time duration of pulsation(sec)	0.2

D. Response Surfaces Methodology

Response surface methodology approach is the procedure for determining the relationship between various process parameters with the various machining criteria and exploring the effect of these process parameters on the coupled responses. In order to study the effect of EDM process parameters of FW4 material on the volumetric metal removal rate and Tool Wear Ratio, a second-order polynomial response can be fitted into the following equation of

$$Y= \beta_0+ \beta_1X+ \beta_2\Phi+ \beta_3\Psi+ \beta_{12}X\Phi+ \beta_{13}X\Psi+ \beta_{23}\Phi\Psi+ \beta_{11}X^2+ \beta_{22}\Phi^2+ \beta_{33}\Psi^2 \quad (3)$$

Where Y is the response and X, Φ, Ψ are the quantitative variables. β_1, β_2 and β_3 represent the linear effect of X, Φ and Ψ respectively, β_{11}, β_{22} and β_{33} represent the quadratic effects of X, Φ and Ψ. β_{12}, β_{13} and β_{23} represent linear-by-linear interaction between "X and Φ" "X and Ψ" "Φ and Ψ" respectively. These quadratic models work quite well over the entire factor space and the regression coefficients were computed according to the least-squares procedure.

IV. Experimental results

Table IV illustrates the order, combination and design of the experiments based on the coded surfaces and results of desired response surfaces (machining characteristics).

TABLE IV
THE MATRIX OF ORDER AND DESIGN OF THE EXPERIMENTS AND THE TEST OUTPUTS

No. of EXE	Current (A)	Pulse-on time (µs)	Voltage (v)	MRR (mm3/min)	TWR (%)	R_a (µm)
1	−1	−1	−1	3.7549	18.1820	3.281
2	+1	−1	−1	12.1110	37.8124	5.196
3	−1	+1	−1	4.6120	6.4570	4.049
4	+1	+1	−1	24.3222	17.9658	5.975
5	−1	−1	+1	7.4420	21.4499	3.413
6	+1	−1	+1	15.8079	46.3980	5.536
7	−1	+1	+1	9.5043	12.2451	4.568
8	+1	+1	+1	30.9182	32.4150	6.788
9	0	0	0	19.5459	18.2180	4.756
10	0	0	0	20.5299	16.8745	4.794
11	0	0	0	19.6183	17.7849	4.768
12	−1	0	0	9.3188	10.3936	3.804
13	+1	0	0	23.3422	30.6535	5.880
14	0	−1	0	12.5013	25.8475	4.227
15	0	+1	0	20.2945	12.5387	5.208
16	0	0	−1	16.6786	15.7617	4.705
17	0	0	+1	22.4833	21.6390	5.073

V. Modeling response variables

The equations 4, 5 and 6 show the models for predictions and calculating MRR, TWR and R_a.

$$SQRT\ (MRR) = -6.6652+0.9576\ I+0.0877\ T_{on}+0.0204\ V-0.0317\ I^2 -0.0019\ T_{on}^2 -0.00002\ V^2 +0.0041\ IT_{on} -0.0004IV+0.00004T_{on}V \quad (4)$$

$$TWR = 68.2491 -3.6317\ I -1.2291\ T_{on} -0.3568\ V+ 0.1974\ I^2+ 0.0137\ T_{on}^2 + 0.0008\ V^2 -0.0178\ IT_{on} + 0.0116\ IV + 0.0012\ T_{on}V \quad (5)$$

$$Ln\ (R_a) = 0.6815+0.0780I+0.0167T_{on} -0.0037V-0.0008I^2-0.0001T_{on}^2 + 0.0001V^2 -0.0002IT_{on}+ 0.0002IV +0.0002T_{on}V \quad (6)$$

Here, I is the peak current, T_{on} is the pulse-on time and V is the spark voltage. Tables V, VI and VIII show the variance analysis results of the introduced models. P values of the models indicate that the assumption of zero model coefficients is rejected not only for an error probability of 5% (α=0.05) but also for the less values of 1% (α=0.01). So, there is at least one sentence in the model, with meaningful effects on machining characteristics.

Tables V, VI and VII also show the values of R^2-statistic and adjusted R^2-statistic. The R Squared (R^2) is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit. The more R^2 approaches unity, the better the model fits the experimental data. For instance, the obtained value of 0.996 for R^2 in the case of TWR (Table VI) implies that the model explains approximately 99.6% of the variability in TWR, whereas R^2 adjusted for the degrees of freedom is 0.992. Also the calculated values of R^2 in Tables V, VI and VII confirm that the relationships between the independent factors and responses can adequately be explained by models.

Table VIII presents the values of β coefficients of models, in order to test the significance of each individual term in the models; a complete analysis of variance according to Student's t-test was performed. The calculated t-values as well as corresponding P-values are listed in Table VII. Table's results show that SQRT (MRR) response is most affected by current. It is also obvious that the quadratic effect of effect of voltage is not significant model terms. For the second response (TWR) that results show a remarkable effect of all the sentences of the model, especially the ones related to the pulse-on time. As can be observed, in the case of R_a all the terms have a significant effect on the response.

TABLE V
VARIANCE ANALYSIS FOR THE MODEL OF THE MRR

Source	Sum of Squares	d.f.	Mean Square	F-value	P-value
Model	16.7259	9	1.8584	1273.6869	<0.0001
Residual	0.01021	7	0.0014		
Total	16.7361	16			
R-Squared	0.9993				
Adjusted R-Squared	0.9986				
Standard Error	0.0381				

TABLE VI
VARIANCE ANALYSIS FOR THE MODEL OF THE TWR

Source	Sum of Squares	d.f.	Mean Square	F-value	P-value
Model	1718.4659	9	190.9406	239.7503	<0.0001
Residual	5.57490	7	0.7964		
Total	1724.0408	16			
R-Squared	0.9967				
Adjusted R-Squared	0.9926				
Standard Error	0.8924				

TABLE VII
VARIANCE ANALYSIS FOR THE MODEL OF THE R_a

Source	Sum of Squares	d.f.	Mean Square	F-value	P-value
Model	0.6060	9	1.9760	24.8241	<0.0001
Residual	0.0001519	7	0.0796		
Total	0.6061	16			
R-Squared	0.9997				
Adjusted R-Squared	0.9994				

Standard Error	0.0046

TABLE VIII
COEFFICIENT VALIDATION TESTING FOR THE THREE RESPONSES

Predictor	Coefficients	T-test	P-value
Response: SQRT(MRR)			
Constant	-6.6652	-17.5786	<0.0001
Current (I_c)	0.9576	25.1827	<0.0001
Pulse-on time(T_{on})	0.0877	14.1993	<0.0001
Voltage (V)	0.0204	4.2384	<0.0004
Quad. I_c ($I_c \times I_c$)	-0.0317	-21.7707	<0.0001
Quad. T_{on} ($T_{on}\times T_{on}$)	-0.0019	-24.7639	<0.0001
Quad. V ($V\times V$)	- 0.00002	-1.5974	0.1542
Interaction ($I_c \times T_{on}$)	0.0041	23.1991	<0.0001
Interaction ($I_c \times V$)	-0.0004	-5.5636	<0.0001
Interaction ($T_{on} \times V$)	0.00004	2.6805	0.0315
Response: TWR			
Constant	68.2491	10.6698	<0.0001
Current (I_c)	-3.6317	-7.1873	0.0046
Pulse-on time(T_{on})	-1.2291	-3.2057	<0.0001
Voltage (V)	-0.3568	-5.1034	0.0156
Quad. I_c ($I_c \times I_c$)	0.1974	7.2387	0.0006
Quad. T_{on} ($T_{on}\times T_{on}$)	0.0137	7.8746	<0.0001
Quad. V ($V\times V$)	0.0008	3.7865	0.0441
Interaction ($I_c \times T_{on}$)	-0.0178	-8.5329	0.0037
Interaction ($I_c \times V$)	0.0116	12.1573	0.0005
Interaction ($T_{on} \times V$)	0.0012	-4.4948	0.0179
Response: R_a			
Constant	0.6815	14.7376	<0.0001
Current (I_c)	0.0780	16.8373	<0.0001
Pulse-on time(T_{on})	0.0167	22.2044	<0.0001
Voltage (V)	-0.0037	-6.4502	<0.0001
Quad. I_c ($I_c \times I_c$)	-0.0008	-4.6817	0.0022
Quad. T_{on} ($T_{on}\times T_{on}$)	-0.0001	-19.9072	<0.0001
Quad. V ($V\times V$)	0.0001	6.7268	<0.0001
Interaction ($I_c \times T_{on}$)	-0.0002	-11.9361	<0.0001
Interaction ($I_c \times V$)	0.0002	2.3452	0.05144
Interaction ($T_{on} \times V$)	0.0002	11.1582	<0.0001

VI. DISCUSSIONS AND THE RESULTS OF THE ANALYSIS

Since the models have enough characteristics for changing data we can study the effect of input parameters on machining characteristic by graphs on the basis of models and predict response changes' values on middle surface of input changes.

A. Effects of the input parameters on R_a

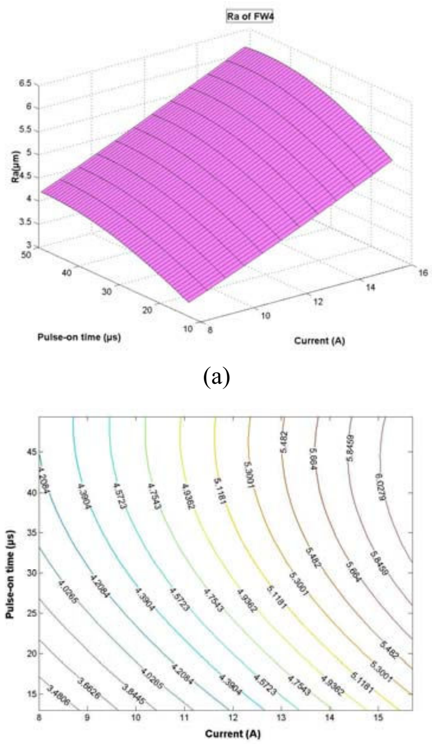
Figures 1(a) and 2(a) plot the predicted value of surface roughness (R_a) in terms of the current, pulse-on time and voltage generated by the regression model. The graph in figures 1(b) and 2(b) are the two-dimensional contour plot obtained by connecting points of constant surface roughness in (I_c-T_{on}) and (I_c-V) planes.

As can be seen in Figures 1 and 2 increasing the current, pulse-on time and voltage leads to increase in R_a and they both have nearly the same effect on the increasing of surface roughness. The estimated response surface also shows the interaction effect of current and pulse-on time. Thus, the tendency of R_a to increase when current is increasing depends on the value of pulse-on time, in such a way that it becomes more intense as we move toward higher values of pulse-on time. It is clear that surface roughness increases with the increase of peak current value. It is believed that the increase in peak current causes an increase in discharge heat energy at the point where the discharge takes place. At this point, a pool of molten metal is formed and is overheated. The overheated molten metal evaporates forming gas bubbles that explode when the discharge ceases, taking molten metal material away. The result is the formation of crater. Successive discharges that have a random nature will result in the formation of overlapped crater, pockmarks and chimneys.

It is observed that for all values of the peak current surface roughness increases with the increase of the pulse-on time in the range of low pulse-on time, settings, and becomes constant when machining of higher values of pulse-on time.

The surface roughness first increases slightly with the voltage and then increases severely with further increase of the voltage.

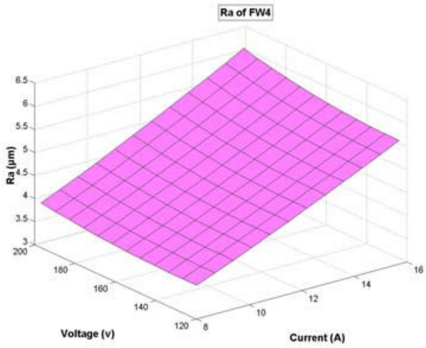
Note from Figures 1 and 2 that if we wish to minimize the surface roughness, we need to run I_c, T_{on} and V at their low values. Furthermore, if we need to obtain a particular surface roughness, for example 4.2 µm, according to Figure 1(b) there are many combinations of current and pulse-on time, on the contour line R_a =4.208 µm, which lead to specified value of R_a.



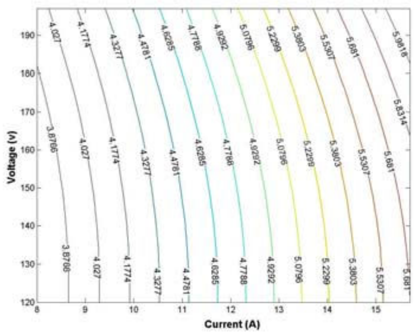
(a)

(b)

Fig. 1 a) Response Surface, b) Contours of the Surface Roughness versus current and pulse-on time (voltage= 160 v)



(a)

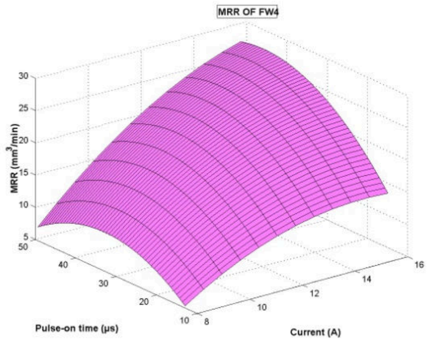


(b)

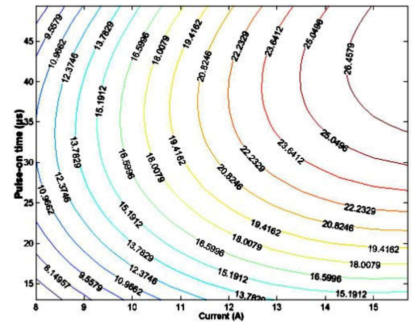
Fig. 2 a) Surface Response, b) Contours of the Surface Roughness versus current and voltage (T_{on}=25μs)

B. Effect of input parameters on MRR

Material Removal Rate in EDM process is an important factor because of its vital effect on the industrial economy. Figures 3 and 4 show the response surface and contour of MRR versus current, pulse-on time and voltage. Increasing the current, pulse-on time and voltage values leads to an increase in the amount of Material Removal Rate. But the most influential factors are peak current and pulse-on time, Also the MRR increase gradually with the voltage. In this process, the spark energy affects the material removal speed and energetic sparks increases the material removal rate Energy of each spark, according to its electrical concepts, is a function of spark current, pulse-on time and voltage. The figures 3(a) and 4(a) show that in all the currents, the MRR decreases after a particular T_{on}. The major reason for the decrease in MRR is high gap pollution and low energy density during pulse-on time. In the view point of industrial economy it is desirable to obtain higher values of MRR, but it should be noted that increase in MRR is usually linked to increase in R_a. Therefore, for a specific value of R_a, the different combinations of input variables (I_c, T_{on} and V), which result in maximum MRR, should be identified (Figures 3 and 4).

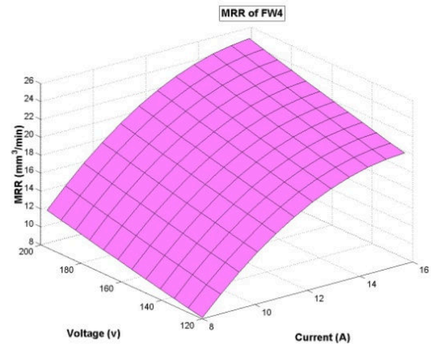


(a)

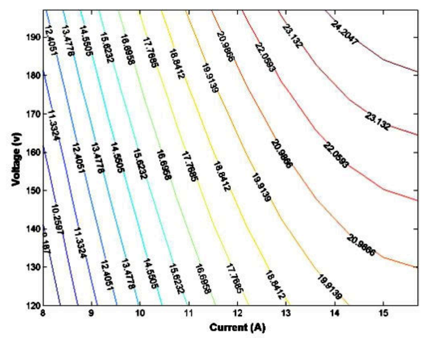


(b)

Fig. 3 a) Response Surface, b) Contours of the material removal rate versus current and pulse-on time (V= 160 v)



(a)

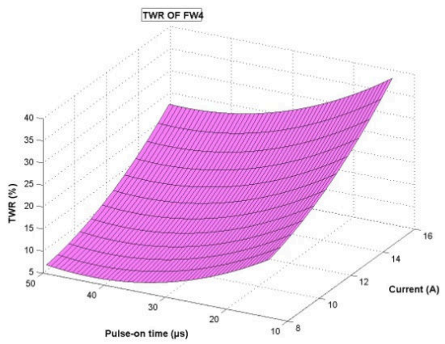


(b)

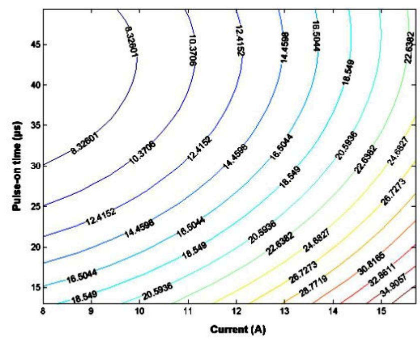
Fig. 4 a) Surface Response, b) Contours of the material removal rate versus current and voltage (T_{on}=25μs)

C. Effects of the input parameters on TWR

Figures 5 and 6 depict the estimated response surfaces for TWR versus peak current and pulse-on time and peak current and voltage, respectively. As one can see in these figures, the wear on the electrode tends to increase when the peak current and voltage are increased, for any value of the pulse-on time. Obviously, the TWR decreases by the increase in pulse-on time, because the motion of electrons overcomes the motion of ions under the positive pole, during the pulse-on time. In the beginning of spark, electrons movement is the major current, and the amount of material removal from the positive pole is more than the negative pole. As the plasma channel spreads, positive ions move more easily and this movement is the most noticeable removal mechanism. The amount of tool wear ratio with longer pulse-on time is lower. So, tool pole proper selection has a major role in EDM machining process. In EDM process, it is important to have high material removal rate and low tool wear ratio at the same time. This is the ideal operating condition. In this condition, contour graphs are regarded as important tools for input parameters selection.

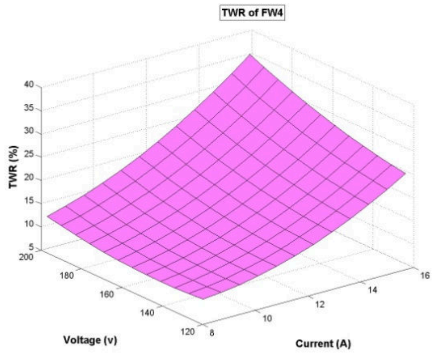


(a)

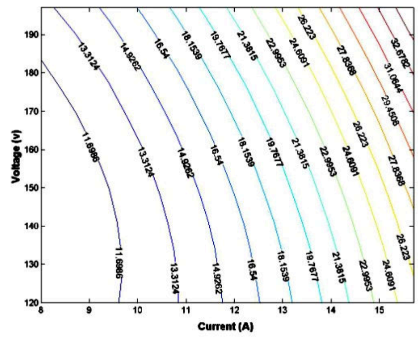


(b)

Fig. 5 a)Surface Response b) Contours for tool wear ratio versus peak current and pulse-on time (V=160v)



(a)



(b)

Fig. 6 a) Surface response b) contour for tool wear ratio versus peak current and spark voltage. (T_{on}=25μs)

VII. Conclusions

In this research, an experimental investigation was performed to consider the machining characteristics in EDM process of FW4 welded steel and the following results were concluded:

1. The regression technique is an important tool for representing the relation between machining characteristic and EDM process input parameters, and the obtained mathematical models, indicate this correlation perfectly.
2. The proper and optimized input parameters to achieve a specific output parameter (MRR, TWR and R_a), and a higher efficiency can be determined by theoretical and experimental characteristic diagrams, especially the tow dimensional contour diagrams.
3. Results show that the central composite design (CCD) is a powerful tool for providing experimental diagrams and statistical-mathematical models, to perform the experiments appropriately and economically.
4. For all values of the peak current, surface roughness increases with the increase of the pulse-on time in the range of low pulse-on time settings, and becomes constant when machining of higher values of pulse-on time.
5. The surface roughness first increases slightly with the voltage and then increases severely with further increase of the voltage.
6. The MRR value first increases with the increase of pulse-on time, but for the values further than a specific T_{on}, it

starts to decrease, affected by some thermodynamic factors, independent of the current value.

7. The increase of pulse-on time results in a decrease of Tool Wear Ratio.

8. The results show that for optimum parameter setting, a compromise should be made between R_a and MRR or TWR.

REFERENCES

[1] www.corewire.com

[2] Fonda, P., Wang, Z., Yamazaki, K, Akutsu, Y., 2007, A fundamental study on Ti–6Al–4V's thermal and electrical properties and their relation to EDM productivity, J. Mater. Process. Technol.,

[3] Mukherjee, I., Ray, P.K., 2006, A review of optimization technique in metal cutting process, Computer & Industrial Engineering, 50: 15-34.

[4] Hewidy, M.S., El-Taweel, T.A., El-Safty, M.F., 2005, Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM, J. Mater. Process. Technol., 169: 328–336.

[5] Puertas, I., Luis, C.J., Álvarez, A., 2004, Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC–Co, J. Mater. Process. Technol., 153–154: 1026–1032.

[6] Puertas, I., Luis, C.J., 2004, A study on the electrical discharge machining of conductive ceramics, J. Mater. Process. Technol., 153–154: 1033–1038.

[7] Puertas, I., Luis, C.J., Villa, G., 2005, Spacing roughness parameters study on the EDM of silicon carbide, J. Mater. Process. Technol., 164–165:1590–1596.

[8] Luis, C.J., Puertas, I., 2007, Methodology for developing technological tables used in EDM processes of conductive ceramics, J. Mater. Process. Technol., 189: 301–309.

[9] Khoshkish, Ashtiani, Goreyshi, Effects of Tool electrode material on electrical discharging machining process of hardened tool AISI D3, Iran Conference of Manufacturing Engineering

[10] George, P.M., Raghunath, B.K., Manocha, L.M., Warrier, A.M., 2007, EDM machining of carbon–carbon composite—a Taguchi approach, J. Mater. Process. Technol., 153-154: 920–924.

[11] www.MVI.com

[12] Montgomery, D.C., 1997, Design and Analysis of Experiments, Wiley, NewYork.