Mathematical Analysis of Electrical Discharge Machining on FW4 Weld Metal

M. R. Shabgard, R. M. Shotorbani and S. H. Alenabi
Department of Mechanical Engineering
University of Tabriz, Iran

Abstract

In this paper a study was carried out to analyze the effects of machining parameters(current, pulse-on time and voltage) on the Material Removal Rate (*MRR*) and Stability factor of the process (S_f).The results of analysis of variance (ANOVA) indicate that the proposed mathematical models, can adequately describe the performance of the process within the range of the factors being studied. Additionally, a novel methodology for detecting and mathematical prediction- modeling of abnormal pulse shapes has been developed, which increases process stability, dramatically. Analyzed results indicated that peak current and voltage are the most significant parameters for *MRR* and Stability factor (S_f) respectively. Experimental results and the predictions based on the developed models further revealed that there is a substantial interaction between current and voltage in terms of MRR. Likewise, the interaction between peak current and pulse on time is the main influencing interaction factor for S_f, in order of importance.

Keywords:
Electrical Discharge Machining (EDM); Linear Regression Technique; Response Surface Methodology (RSM)

Introduction

In recent years, metalworking industries have shown great interest in improving service life of tools used in hot working operations, such as hot forging. These processes are characterized by working temperatures higher than 600ºC and large loads about 5000 Tons(Castro et al 2007). In this way, hot working tools are subjected to continuous mechanical and thermal loadings, which finally lead to a heavy damage of the tool surface due to wear, plastic deformation and thermal and mechanical fatigue. Thus, forging dies have to be replaced after a certain time of use, leading to considerable costs associated to machining of tools and set-up times which in turn decrease the productivity. In order to minimize wear, thermal fatigue crack and rupture of forging dies, Iran Tractor Forging Co. one of the major forging industries in the Middle East, had launched a project to replace the long used AISI H11, H13 and H19 -Hotwork- Tool Steels with a newly developed Welded Metal (Preciado et al 2006). FW4 is a weld metal which is the most important and applicable weld material on the basis of chromium. Using weld 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 tool steels. Also it causes a decline in materials and mould's expenses to 62% compared with the dies made of AISI H1-H19 Tool Steels. In this technique, first of all, the parent metal's type and grade should be determined. Then the place of insert of the cavity is removed by milling and/or cutting operations and using special wires, this place is filled by welding processes. After this stage the welded surface is face-milled and grinded (Fig.1).

The FW4 Welded Metal owns a good resistant to the high temperature, wear, and thermal fatigue crack, with a hardness spam of 30–50 HRC. The mentioned reasons vindicate the advantage of using FW4 Welded Metal in making forging dies .In order to machine such workpieces which are hardened, during the welding process, EDM is used vastly, considering its machining capabilities.

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 (Mukherjee et al. 2006) Moreover, Regression analysis is regarded as a powerful tool for representing the correlation between input parameters and process responses in comparison with the other modeling methods(Puertas et al 2004).

Payal et al. (2010) performed some experiments on EN-31 tool steel with copper, brass and graphite as tool electrodes with kerosene oil as dielectric fluid to determine EDmaching most influential process parameters.

Graphite electrode machined specimens show volcanic eruption and cracks due to non-uniform distribution of heat on work surface. An analysis has been done by Khan to evaluate the electrode wear material removal rate during EDM of aluminum and mild steel using copper and brass electrodes. It was found that the MRR increases sharply with increase in current (Khan 2008). Using Taguchi method and Grey relational analysis, N. Natarajan et al.(2011) presented optimization of multiple performance characteristics in micro electrical discharge machining of 304 satainless steel. Based on confirmation test, improvment in performance charachteristics were found. Habib and Sameh (2009) has highlighted the development of a comprehensive mathematical model for correlating the interactive and higher order influences of various electrical discharge machining parameters through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. Marafona and Araújo (2009) used The Taguchi methodology to study the influence of the hardness of the AISI/SAE-D2 alloy steel on the material removal rate and on the workpiece surface roughness in Edmachining. This research leads to desirable process outputs (MRR and Stability factor *(S_f)*) by optimum selection of the cited input parameters(current and pulse-on time).

1. Testing Procedure

1.1. 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.

To control the process, monitoring of input parameters and recording of EDM pulses an electronic circuit was designed and made. This electronic circuit was employed to capture the gap voltage and current variations against time, which were then transferred and stored on a PC hard disk through a serial cable and port connection. The schematic diagram of the experimental setup is demonstrated in figure 2. Additionally, in order to count the number of each type of pulses, a programme in Fortran language was written and linked to the pulse monitoring software (ITM). The material used for workpiece was FW4 weld metal (Table 1).

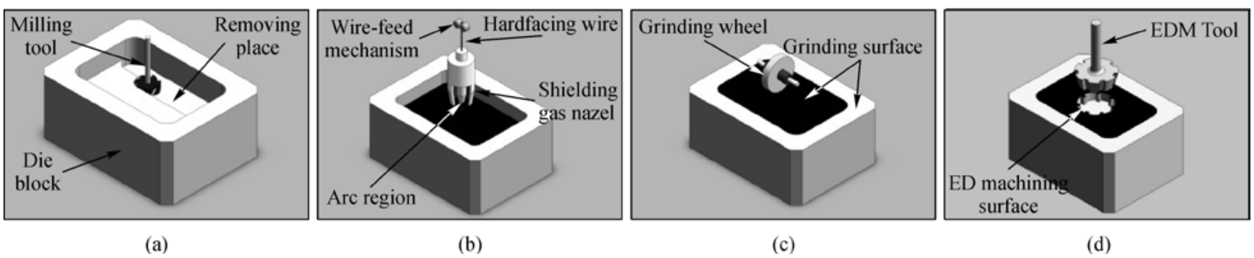

Figure 1: Schematic diagram of production route of molds made of weld metal. (a) Mill-removing of the insert's place; (b) MIG-welding of the insertplace; (c) grinding of the mold face; (d) ED machining of the mold.

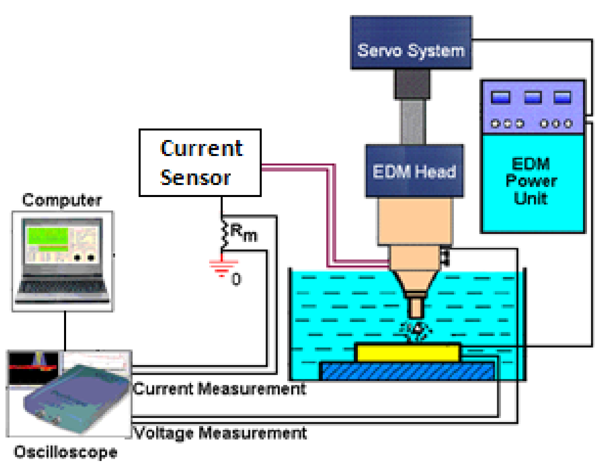

Figure 2: Schematic diagram of the experimental setup

Table 1. Chemical composition of the working material

Material Analysis of FW4 (% weight)											
C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	W	Ti
0.188	0.483	0.017	0.013	0.973	1.628	8.963	2.400	0.035	0.050	0.026	0.099
As	Sn	Co	Al	Pb	Sb	Nb	Zr	Bi	Ca	Zn	Fe
0.019	0.007	0.015	0.06	0.008	0.003	0.013	0.004	0.012	0.003	0.0178	84.988

Table 2. Workpiece and tool Electrodes physical properties

Properties of FW4 (Workpiece)		Properties of EC-16 (Graphite Tool)	
Density	7.7623 (×1000 kg/m^3)	Bulk Density	1.811 (g/cm^3)
Melting point	2670 (˚C)	Specific Resistance	1650 (µohm-cm)
Poisson's Ratio	0.34	Flexural Strength	750 (kg/cm^2)
Elastic Modulus	210 (GPa)	Shore Hardness	70
Hradness	45.5 HRC		
Thermal Conductivity	27.2(W/m.K)		

2. Design of Experiments

There are a large number of factors to consider within the EDM process, but in this work peak current (I_c) and pulse-on time (T_{on}) have only been taken into account as design factors. The EDM process stability is determined by the proportion of abnormal discharges in the gap between a workpiece and an electrode, i.e. arc discharges and open-circuits, which not only lower the material removal rate, but also increase the tool wear. The *%NNP*, *%NOC* and *%NAD* symbols were defined according to the following rules:

$$\%NNP = \frac{Number\ of\ \ Normal\ Pulses}{Number\ of\ \ all\ \ pulses} \times 100 \tag{1-1}$$

$$\%NOC = \frac{Number\ of\ \ Open\,Circuits}{Number\ of\ \ all\ \ pulses} \times 100 \tag{1-2}$$

$$\%NAD = \frac{Number\ of\ \ Arc\ Discharges}{Number\ of\ \ all\ \ pulses} \times 100 \tag{1-3}$$

Moreover, the S_f parameter which is represented the Stability factor of EDmachining process, is evaluated using equation (2):

$$Sf = \frac{\%NNP}{\%NOC + \%NAD} \tag{2}$$

where S_f is the stability factor of the process.

2.1. Fractional factorial design employed

Experiments were designed on the basis of the experimental design technique that has been proposed by Box and Hunter [15]. The design which was finally chosen was a factorial design 2^3 with three central points, which provide protection against curvature, and a total of 11 experiments were made Consequently, for the case of the response variables which were not adequate for the previous first order model, this was widened by the addition of six star points, giving then a central composite design made up of the star points situated in the centers of the faces; that is to say, a total of 17 experiments in the case of this second order model. A summary of the levels selected for the factors to be studied is represented in Table 3. In addition, all the experimental conditions and variables considered in the tests are listed in Table 4. Table 5 depicts 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*, and S_f. 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.

3. 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 input parameters of FW4 on *MRR*and S_f a second-order polynomial response can be fitted into the following equation:

$$Y= \beta_0+ \beta_1 X+ \beta_2 \Phi+ \beta_3 \Psi+ \beta_{12} X\Phi+ \beta_{13} X\Psi+ \beta_{23} \Phi\Psi+ \beta_{11} X^2+ \beta_{22} \Phi^2+ \beta_{33} \Psi^2 \quad (3)$$

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.

Table 3. Factors and levels selected for the experiments

Factors	Levels		
	-1	0	+1
Current (A)	8	12	16
Pulse-on time (µs)	12.8	25	50
Voltage (v)	120	160	200

Table 4. Experimental conditions and process variables

Condition and variables	Description
Generator type	Iso pulse
Workpiece	FW4 Weld metal (20 mm diameter and 20 mm length)
Tool	Graphite Ec-16 (18 mm diameter and 20 mm length)
Tool polarity	Positive
Dielectric	Oil Flux ELF2
Flashing type	Normal submerged
Gap (µm)	0.09
Current (A)	8,16,24
Pulse-on time (µs)	12.8,25,50
Voltage (v)	120,160,200
Reference voltage (v)	70
Pulse-off time (µs)	6.4

4. Experimental Results

Table 5 illustrates the order, combination, design of the experiments and results of desired response surfaces (machining characteristics).

4.1. Modeling response variables

The equations 4 and 5 show the models for predictions and calculating *MRR* and S_f.

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

$$Exp\ (S_f)= 0.8438 -0.0320\ I_c +0.0047\ T_{on} +0.0069\ V +0.0018\ I_c^2 -0.000050\ T_{on}^2 -0.0000076\ V^2 -0.00026\ I_c.T_{on} -0.00025\ I_c.V +0.000026\ T_{on}.V \quad (5)$$

where, I_c is the peak current (A), T_{on} is the pulse-on time (µs) and V is the spark voltage (v). Tables 6 and 7 show the variance analysis results of the introduced models. The P-value for each model in, mentioned tables is less than 0.05, indicating that for a confidence level of %95, the models are statistically significant and terms in the model have the significant effect on the responses.

Table 5. The matrix of order and design of the experiments and the test outputs

No. of EXE	I_c(A)	T_{on} (μs)	I (v)	*MRR* (mm^3/min)	S_f
1	−1	−1	−1	3.7549	0.231
2	+1	−1	−1	12.1110	0.072
3	−1	+1	−1	4.6120	0.301
4	+1	+1	−1	24.3222	0.114
5	−1	−1	+1	7.4420	0.397
6	+1	−1	+1	15.8079	0.143
7	−1	+1	+1	9.5043	0.513
8	+1	+1	+1	30.9182	0.222
9	0	0	0	19.5459	0.245
10	0	0	0	20.5299	0.235
11	0	0	0	19.6183	0.245
12	−1	0	0	9.3188	0.375
13	+1	0	0	23.3422	0.154
14	0	−1	0	12.5013	0.203
15	0	+1	0	20.2945	0.288
16	0	0	−1	16.6786	0.159
17	0	0	+1	22.4833	0.294

Furthermore, Tables 6, and 7 demonstrate 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 unify, the better the model fits the experimental data. For instance, the obtained value of 0.993 for R^2 in the case of *MRR* (Table 6) implies that the model explains approximately 99.3% of the variability in *MRR*, whereas R^2 adjusted for the degrees of freedom is 0.998. Also the calculated values of R^2 in Tables 6 and 7 confirm that the relationships between the independent factors and responses can adequately be explained by the models. The adjusted R^2 is a modification of R^2 that adjusts for the number of explanatory terms in the model and the adjusted R^2 increases only if the new term improves the model more than would be expected by chance. Adjusted R^2 does not have the same interpretation as R^2 and it can be negative, and will always be less than or equal to R^2 (Montgomery 1997). Table 8 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 8. Table's results show that SQRT (*MRR*) response is most affected by current. It is also obvious that the most influencing interactions is $I_c \times T_{on}$ and the quadratic effect of voltage is not significant model terms. In the case of Exp (S_f) the coefficients for $I_c \times V$ and the quadratic effect of V is negligible respectively and therefore its effect is not significant for the cited models.

Table 6. 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 7. Variance analysis for the model of the S_f

Source	Sum of Squares	d.f.	Mean Square	F-value	P-value
Model	0.34144	9	0.0379	285.6286	<0.0001
Residual	0.00092	7	0.0001		
Total	0.34237	16			
R-Squared	0.99728				
Adjusted R-Squared	0.99379				
Standard Error	0.01152				

5. Discussion

5.1. Effect of input parameters on *MRR*

Material Removal Rate in EDM process is of the crucial importance, considering its vital impact on economical production. Figures 3 and 4 represent the response surfaces of *MRR* versus current, pulse-on time and voltage.

Table 8. 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: *Exp*(S_f)			
Constant	0.8438	7.3766	<0.0001
Current (I_c)	-0.0320	-2.7917	0.0268
Pulse-on time(T_{on})	0.0047	2.5365	0.0388
Voltage (V)	0.0069	4.8092	0.0019
Quad. I_c ($I_c \times I_c$)	0.0018	4.21388	0.0039
Quad. T_{on} ($T_{on} \times T_{on}$)	-0.000050	-2.1624	0.0673
Quad. V ($V \times V$)	-0.0000076	-1.7376	0.1258
Interaction ($I_c \times T_{on}$)	-0.00026	-4.8394	0.0018
Interaction ($I_c \times V$)	0.00025	-9.9951	<0.0001
Interaction ($T_{on} \times V$)	0.000026	4.9742	0.0016

The increase of current, pulse-on time and voltage values leads to an increase in the amount of Material Removal Rate. But the most substantial factors are peak current and pulse-on time. Additionally, *MRR* increase slightly with the voltage. Moreover, figures 3 exhibits the interaction between two different machining parameters (I_c and T_{on}, which is also confirmed by the ANOVA Table 8). An interaction between factors takes place when the variation in response from a level of a factor to another level varies from the change in response at the same two levels of a another factor; this implies that the effect of one factor is dependent upon another factor.

This figure indicates that an increase in discharge pulse duration time gives an initial significant increase in material removal rate and the further increase only leads to a very slight rise in material removal rate. The explanation for the *MRR* behavior after its maximum point is concerned to very high plasma diameter expansion due to the long discharge duration T_{on}, that diminishes pressure and energy of the plasma channel over the molten material of the electrodes. As a consequence, this phenomenon brings instability to the process lowering the material removal rate. Moreover, high gap pollution and low energy density during high pulse-on time values lead the *MRR* to descend.

Moreover, It can be noticed that an increase of gap voltage causes an increase in the volumetric metal removal rate slightly. The increase in voltage means applying higher heating flux in a same period of time. This will cause an increase of heat that is conducted into the workpiece as the plasma channel expands which will result in an increase in the MRR.

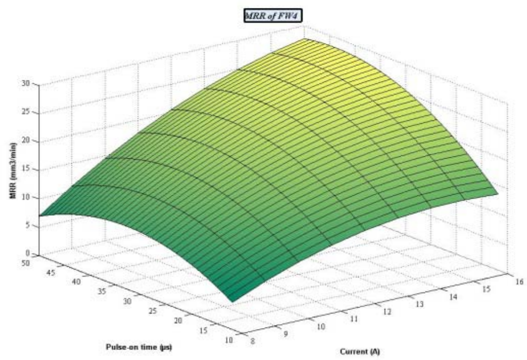

Fig. 3: Response Surface of the Material Removal Rate versus current and pulse-on time (V= 160 v)

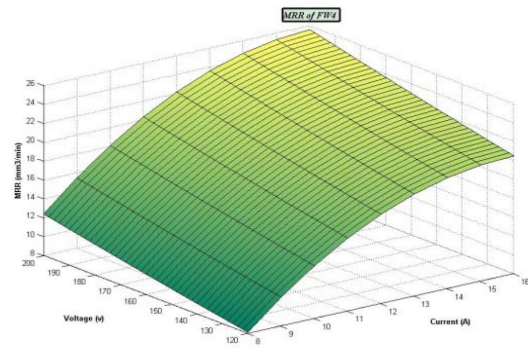

Fig. 4: Surface Response of the Material Removal Rate versus current and voltage (Ton=25µs)

5.2. Effects of input parameters on process stability and pulse shape

Spark-erosion processes have often been analyzed and controlled by real time detection and evaluation of discharges in the gap. In this research during the experiments, information of pulse types was stored in PC. The detecting waveforms were plotted to elucidate the delay time and the abnormal electrical discharge, during EDM. Moreover, eachappearing discharge is analyzed, and pulse characteristics are compared with preset values.

Figure 5 and 6 show the predicted value of Stability factor (S_f) of the process in terms of the current, pulse-on time and the voltage, generated by the regression model for the EDmachining of FW4 welded metal.

It is evident that, there is an overall trend to decrease of the stability of the process by altering the process mode to roughing regimes. Furthermore, theses figures reveal that the ratio of normal pulses to abnormal discharges (S_f) in EDmachaning of FW4 depends on the values of current, considerably. It is also noticeable from the same figures that the pulse-on time and voltage has a limited effect on the S_f, whereas the cited parameters caused a positive impact on the stability of the process. The results detailed above were confirmed by t-test data given in Table 8.

However, figures 7 and 8 portray the different discharging waveforms and the corresponding discharging effect for the different input parameters. It is obvious from figure (a) that the occurrence of open-circuit pulses is the most considerable phenomenon in finishing modes. Gap conditions in EDM are random in nature in terms of dielectric condition and gap size. In fishing modes, the control of the process is difficult, because in these stages the gap between the electrodes becomes smaller. So the control system has to regulate a smaller gap. This makes the control task more complex and accumulated debris may build a bridge between the electrodes, allowing short-circuit to occur. Moreover, reactions of control system to occurrence of short-circuit pulses leads to the occurrence of open-circuit pulses.

In addition, it is clear that in higher values of input parameters (Fig. 7 (b) and Fig. 8 (a)), the delay time (T_d) of each pulse is plummeted, and occurrence of normal pulses is increased, consequently. It is due to the increase of Material Removal Rate and debris aggregation because of the increase in pulse Energy, in higher setting values. However, additional debris into the kerosene may enlarge the gap. This is because the additional debris facilitates the bridging effect and minimizes the insulating strength of the dielectric fluid, thus a discharging channel is easily formed and the delay time and the gap voltage between the electrode and the workpiece are considerably decreased. It leads to decreasing of short-circuit and open-circuit pulses' occurrence.

By further increase of pulse-on time, it is noticed that much instability was brought into the working gap in either the form of arc discharge pulses, probably due to insufficient interval time T_d between to successive discharges to evacuate the coarse eroded material and simultaneously de-ionize the working gap (Fig. 8 (b)). As a consequence the overconcentration of dielectric and electrodes byproducts negatively interfered on the occurrence of normal discharges. Collection of debris in sparking gap, impurity, different compounds of hydrocarbons that are decomposed from hydro-carbonaceous dielectric and presence of decomposed gases (such as carbon monoxide, methane, etc) prepare an especial condition that increase the arc pulses' occurrence and reduces machining efficiency. Therefore, it should be noted that when I_c, T_{on} or V are increased the *MRR* parameter also tends to increase at least up to a maximum value (peak point), after which it tends to decrease due to that the increase of abnormal discharges overcome the rising of pulse energy.

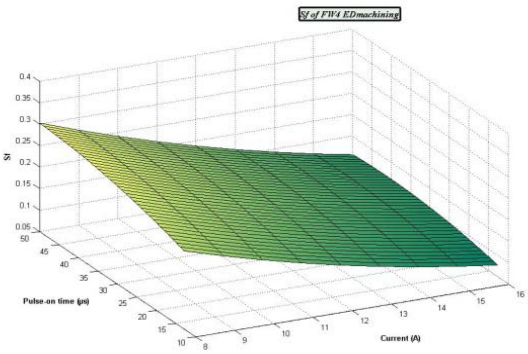

Fig. 5: Response Surface of the Stability factor versus current and pulse-on time (V=160 v)

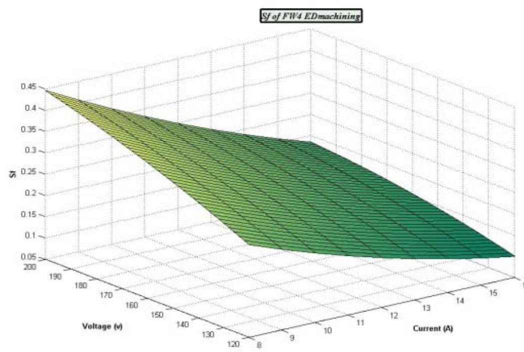

Fig. 6: Surface Response of the Stability factor versus current and voltage (T_{on}=25µs)

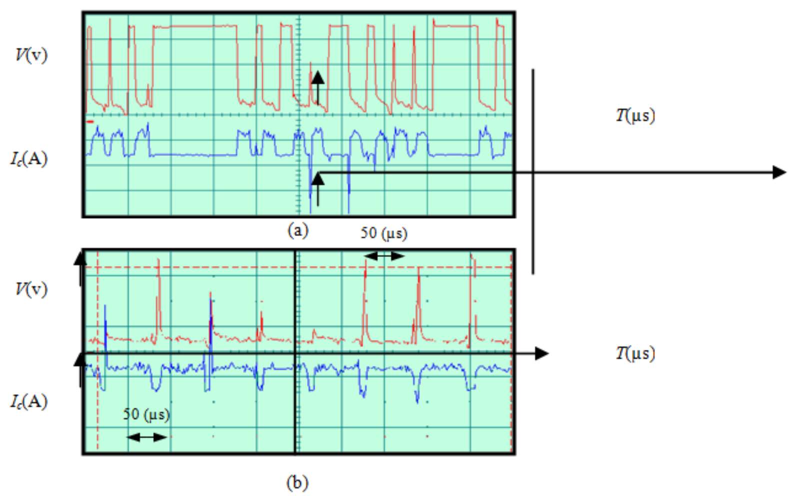

Fig. 7: Typical records of pulse shapes, a) T_{on}=12.8µs, b) T_{on}=50µs (I_{C}=8A, V=200v)

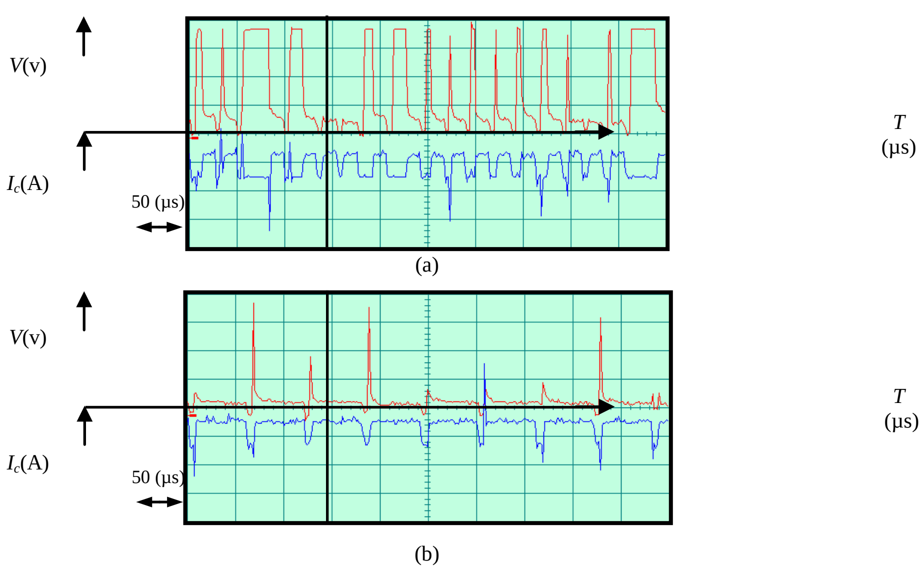

Fig. 8: Typical records of pulse shapes, a) T_{on}=12.8µs, b)T_{on}=50µs (I_C=16A, V=200v)

6. Optimum Parameter Settings

Optimum of the EDM process should be regarded as a multivariate, multicriteria problem in which the goal is to minimize or maximize not a single multivariate response function but several functions simultaneously with conflicting effects. After fitting a second-order model as a response, it would be very useful to identify the proper combination of parameters by means of contour plots which one of the most revealing ways of illustrating the response surface system. The overlaying of contour plots along with separate response surface analyses often give workable solutions for optimum parameter settings as long as the number of responses and input variables or parameter are less than four. The graph in figure 9 is a two-dimensional contour plot obtained by connecting points of constant Responce variable (*MRR*) in I_c-T_{on} plane.

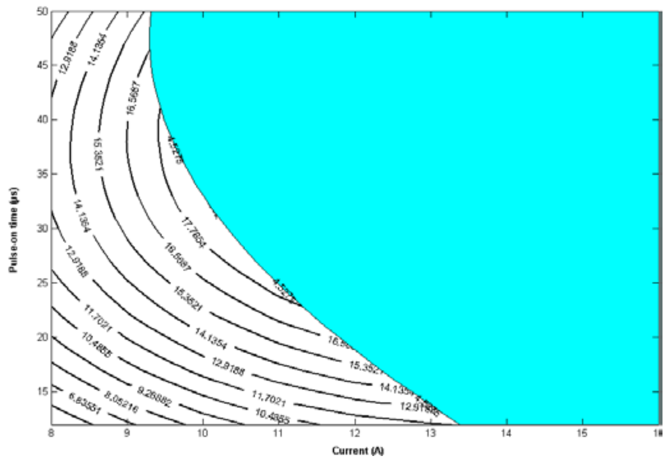

Fig. 9: A typical overlay plot of *MRR*

The white area in Figure 9 defines the permissible region which includes different combinations of input parameters for I_c and T_{on}. As it can be seen on the figure 9, there is a group of contour lines of *MRR* passing through the white area which corresponds to a range of *MRR* values.

7. Conclusions

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

1. It has been confirm that the regression technique can be successfully applied to model the input and output variable of electro discharge of FW4 weld metal.
2. Within the scope of this experiment, 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.
3. It is obvious that in lower values of pulse-on time and pulse current, the occurrence of open-circuit pulses is the most considerable phenomenon.But In higher values of pulse current (roughing modes), the level of arc pulses extremely increases.
4. Utilizing the pulse shape detection facility and a novel mathematical prediction model have eventuated in that the detrimental influence of unsuitable selection of adjustable machining parameters has been mitigated. It can be suggested the proper levels of machining setting to establish a highly-efficient process, dexterously.
5. The proper and optimized input parameters to achieve a specific output parameter (MRR) and a higher efficiency can be determined by theoretical and experimental characteristic diagrams, especially the two dimensional contour diagrams.

Acknowledgements

The authors would like to express their gratitude to the Iran Tractor Foundry Company for supporting this research.

References

Castro, G., Fernández-Vicente, A., Cid, J., (2007), Influence of the nitriding time in the wear behavior of an AISI H13 steel during a crankshaft forging process, J.Wear, Vol. 263, pp. 1375–1385.

Habib,Sameh S., (2009),Study of the parameters in electrical discharge machining through response surface methodology approach,Applied Mathematical Modelling, vol. 33, pp. 4397–4407.

Khan, A.A., (2008),Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes,Int. J. Manuf. Technol., vol. 39,pp. 482–487.

Marafona, J.D., and Araújo, A., (2009), Influence of workpiece hardness on EDM performance, International Journal of Machine Tools & Manufacture, vol. 49, pp. 744–748.

Montgomery, D.C., (1997), Design and Analysis of Experiments, Wiley, NewYork.

Mukherjee, I., Ray, P.K., (2006), A review of optimization technique in metal cutting process, Computer & Industrial Engineering, vol. 50, pp. 15-34.

Natarajan, N., and Arunachalam, R.M.,(2011),Optimization of micro-EDM with multiple performance characteristics using Taguchi method and Grey relational analysis, J. Science & Industrial Research (JSIR), vol. 70, pp. 500–505.

Preciado, W.T., Bohorquez, C.E.N., (2006), Repair welding of polymer injection molds manufactured in AISI P20 and VP50IM steels, J. Mater. Process. Technol., vol. 179, pp. 244–250.

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., vol. 153–154, pp. 1026–1032.

Payal, H.S., Choudhary, R., Singh, S., (2010), Analysis of electro discharge machined surfaces of EN-31 tool steel, J. Science & Industrial Research (JSIR),vol. 17, pp. 91-97.