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Investigating the Effect of Machining Parameters on EDMed Components a RSM Approach

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ABSTRACT

The effects of the machining parameters in electrical-discharge machining on the machining characteristics of AISI D2 steel workpiece has been investigated in this research. The response functions considered are Material Removal Rate (MRR) and surface roughness (Ra), while machining variables are pulse current, pulse on time, pause time and gap voltage. A Response surface methodology was used to reduce the total number of experiments. Empirical models correlating process variables and their interactions with the said response functions have been established. The significant parameters that critically influenced the machining characteristics were examined and developed predictive models. Analyzing these models, it is found that pulse current is the most significant parameter for both the responses, followed by pulse off time, gap voltage and pulse on time for MRR, and pulse on time and gap voltage for Ra. The model sufficiency is very satisfactory as the coefficient of determination (R^2) is found to be greater than 98.3% and R^2_{adj} is over 97.6%. These models can be used for selecting the values of process variables to get the desired values of the response parameters

Keywords: *Electrical-discharge machining, Material removal rate; Surface roughness; Response surface methodology*

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Introduction

In the present day's manufacturing scenario, the demand for advanced materials with high strength, high toughness and hardness are vital. Therefore, the new types of advanced materials have been invented for various industrial applications. These advanced materials usually have excellent mechanical properties to satisfy the necessities of applications that are usually used in harsh environments. To work with such components, made by the newly developed materials with excellent mechanical properties, faces critical problems. Conventional processes for machining advanced materials encounter several hindrances, so the conventional processes are becoming insufficient as they are associated with poor machining efficiency, precision and quality in current industrial applications. Hence, non-conventional processes, such as EDM, provide attractive alternatives for "difficult-to-machine" materials. The material removal mechanism of the EDM process is not regulated by mechanical force, so the machining characteristics of the EDM process are not governed by the mechanical properties of the work piece material. Indeed, the work piece material is removed by a local high temperature associated with a very high energy density caused by ionization within the discharge column between the work piece and electrode. Hence, the material removal mechanisms of the EDM process are thermal erosion, such as that due to melting and vaporization. Moreover, the cost of the equipment used in the EDM process is cheaper than that used in other non-conventional processes. This process is an extremely complex phenomenon to which scientific knowledge is incomplete both at macroscopic as well at the microscopic level [1]. Thus the mechanism of material removal of EDM process is not yet completely understood. To be aware of the process in better way, modeling of the process have been carried out by the researchers. Erden et al. [2] reviewed the mathematical models, Tariq and Pandey [3] employed heat transfer model to study the input parameter on Material Removal Rate (MRR). However, most previous theoretical studies have been concerned with microscopic metal removal arising from a single spark, the effects being modeled from heat conduction theory and thermodynamic considerations. The complicatedness of EDM physical modeling has aggravated the use of data-driven or empirical methods in which the process is analyzed using statistical techniques. Ghoreishi and Atkinson [4] employed statistical modeling and process optimization for the case of EDM drilling and milling. They compared the results and concluded that the model gives satisfactory results when the most usual combination of requirements was considered in an optimization procedure. In another study, Wang and Tsai [5, 6] proposed semi-empirical models for the MRR, surface finish, and tool wear on the work piece and the tool for various materials in EDM, employing dimensional equations based on relevant process parameters for the screening experiments and the dimensional analysis. Effects of EDM process parameters have been investigated. Wang and Yan [7], Lin et al. [8] and Lin and Lin [9] studied the effect of current, polarity, voltage, and spark on-time on the EDM process by using the Taguchi method. Lee and Li [10] studied the effects of process parameters in EDM of tungsten carbide. Hocheng et al. [11] considered the correlation of current and spark on-time and the crater size produced by a single spark of SiC/Al work-material. Qu et al. [12, 13] examined the EDM process parameters in a cylindrical EDM process. A number of researchers have applied RSM to manufacturing environments. Some very useful work reported in the literature include, the investigation of controlled electrochemical machining using the response surface methodology-based approach [14] developing mathematical models for optimizing electric discharge machining characteristics [15].

The machining parameters of EDM are many, so conducting conventional single-factor experiments to reveal the effects of all of them on EDM performance is expensive and time-consuming. Thus this investigation was conducted using the RSM, which provides the result with very few experiments. This paper attempts to develop empirical models, using RSM, as functions of pulse current (Ip), pulse on time (Ton) and gap voltage (V), for the response parameters MRR and surface roughness (Ra). A series of experiments are conducted, using die sinking EDM with an electrolytic copper electrode on AISI D2 steel. The experimental data were statistically analyzed by analysis of variance (ANOVA) and the F-test to determine the significant parameters associated with each response variable.

Experimental Details

The experiments were conducted on an Electronica Elektra plus PS 50ZNC die-sinking EDM machine. The tool electrode (of positive polarity) material used in the EDM process was 30 mm diameter electrolytic pure cupper. Furthermore, the tool electrodes were selected in a prismatic form with a transverse area of 35×35 mm^2 and thickness of 4 mm (with negative polarity). The selected workpiece material for the research work is AISI D2 (DIN 1.2379) tool steel density (7.7g/cc) D2 steel is selected due to its growing range of applications in the field of manufacturing tools in mould industries. It can be classified as a difficult-to-cut material, not suitable for traditional machining. During machining, Commercial grade EDM oil (specific gravity = 0.763, freezing point = 94 C) was used as dielectric fluid. Lateral flushing with a pressure of 0.3 kgf/cm^2 was used with side flushing technique. The machining time for all experiments was kept constant at 15 min. The machining condition and fixed parameters are also listed in Table 1. These were chosen through reviews of experience, literature surveys, and some preliminary investigations.

Table 1: Input Parameters and Their Levels

Parameters	Level		
	1	2	3
Ip (A)	5	10	15
Ton (ìs)	50	75	100
Toff (ìs)	80	100	120
Voltage (V)	40	45	50

Design of Experiments

Design of experiments is a powerful analysis tool analyzing the influence of process variables over some specific variable, which is an unknown function of these process variables. It is the process of planning the experiments so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions. Statistical approval to experimental design is necessary to draw a meaningful conclusion from the data (Montgomery, 2003).

Experimental Plan

Response surface methodology (RSM) is an interaction of mathematical and statistical techniques for modeling and optimizing the response variable models involving quantitative independent variables. In the present work, the range Ip, Ton, Toff and V setting have been selected after performing some pilot experiments. Actual and coded values of the input process parameters have been listed in Table 1. Experiments have been carried out according to the experimental plan based on central composite second-order design (CCD). The CCD consists of fractional factorial points with 16 corner points, eight axial points, and six center points (Montgomery, 2003). Design of experiment matrix showing coded and actual values of the input process parameters is shown in Table 2. The general second order polynomial response surface mathematical model, which is given below is considered to determine the parametric influences on the various response criteria.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

Where Y is the corresponding response, X_i is the input variables, X^2_{ii} and X_iX_j are the squares and interaction terms, respectively, of these input variables. The unknown regression coefficients are β_o, β_i, β_{ij} and β_{ii} and the error in the model is depicted as ε.

Measurement of Response

A. Material removal rate and surface roughness

The parameter MRR was selected as response variable, which refers to the machining efficiency of the EDM process and defined as follows.

$$MRR(mm^3/\min) = \frac{\text{weight of workpiece}}{\text{time of machining}} \times \frac{1}{\text{density of the workpiece material}} \quad (2)$$

The workpiece was weighed before and after each experiment using an electric balance (Sartorius, Japan) with a resolution of 1 mg to determine the value of MRR. For efficient evaluation of the EDM process, the larger MRR is regarded as the best machining performance. In addition to MRR, other very important response variables which is of interest when studying EDM processes, is Ra. Roughness measurement was carried out using a portable stylus type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The profilometer was set to a cut-off length of 0.8 mm, filter 2CR, and traverse speed 1 mm/s and 4 mm evaluation length. Roughness measurements, in the transverse direction, on the workpieces were repeated four times and average of four measurements of Ra parameter values was recorded. The measured profile was digitized and processed through the dedicated advanced surface finish analysis software Talyprofile for evaluation of the roughness parameters. Ra is an important parameter in the EDM process. The parameters that effect roughness are Ip, Ton, Toff, and V. It is a measure of the technological quality of a product, which mostly influence the manufacturing cost of the product. It is defined as the arithmetic value of the profile from the centerline along the length. This can be express as.

$$Ra = \frac{1}{L} \int |y(x)|\, dx \quad (3)$$

Where L is the sampling length, y is the profile curve and x is the profile direction. The average 'Ra' is measured within L = 0.8 mm. Centre-line average 'Ra' measurements of electro-discharge machined surfaces were taken to provide quantitative evaluation of the effect of EDM parameters on surface finish.

Mathematical Modeling and Checking the Adequacy Based on RSM

A. Model for material removal rate

A comprehensive model based on Equation 4 has been developed to correlate the interaction and higher-order effects of the previously mentioned process parameters on MRR utilizing relevant experimental data from Table 2 during the course of machining for such purposes as varying parametric combinations. The mathematical relationship thus obtained for analyzing the influences of the various dominant machining parameters on MRR is given by:

$$Y_{(MRR)} = -57.648 - 4.445Ip + 0.5307Ton + 0.623\,Toff + 0.8648V + 0.4432\,Ip^2$$
$$+ 0.0340\,Ip \times on - 0.041\,Ip \times Toff - 0.04\,Ton \times Toff - 0.0082\,Ton \times V \qquad (4)$$

Table 2: Experimental Layout for the Central Composite Design

Run Order	Ip (A)	Ton (μs)	Toff (μs)	Voltage (V)	MRR (mm³/min)	Ra (μm)	Run Order	Ip (A)	Ton (μs)	Toff (μs)	Voltage (V)	MRR (mm³/min)	Ra (μm)
1	10	75	100	45	10.35	5.55	16	5	100	80	50	4.35	5.59
2	10	75	100	45	9.04	5.98	17	15	100	120	50	33.11	9.01
3	15	50	120	50	29.16	8.43	18	15	50	80	40	29.74	10.49
4	5	50	80	50	5.18	5.01	19	10	75	100	45	8.42	6.54
5	5	100	120	40	5.25	5.03	20	15	50	120	40	20.01	12.01
6	15	50	80	50	33.10	7.43	21	10	75	100	40	8.94	8.2
7	5	50	80	40	4.616	4.59	22	10	75	120	45	9.36	7.13
8	5	50	120	40	8.87	4.71	23	10	75	100	50	11.01	6.35
9	15	100	80	50	51.09	8.1	24	15	75	100	45	33.08	9.68
10	10	75	100	45	8.95	6.12	25	10	50	100	45	9.18	5.87
11	5	100	80	40	4.35	4.89	26	10	75	100	45	11.01	6.25
12	15	100	80	40	51.01	10.93	27	5	75	100	45	5.36	6.07
13	5	100	120	50	6.97	5.7	28	10	100	100	45	10.43	7.27
14	15	100	120	40	33.02	12.49	29	10	75	80	45	9.25	5.92
15	5	50	120	50	14.12	5.19	30	10	75	100	45	9.35	6.75

Table 3: ANOVA Table of MRR and Ra

Estimated Regression Coefficients for MRR					Estimated Regression Coefficients for Ra (μm)				
Term	Coef	SECoef	T	P	Term	Coef	SECoef	T	P
Constant	-57.6480	14.743	-3.910	0.001	Constant	32.814	15.0505	2.180	0.041
Ip	-4.4447	0.708	-6.278	0.000	Ip	1.046	0.2317	4.516	0.000
Ton	0.5307	0.177	2.987	0.007	Ton	0.012	0.0032	3.679	0.001
Toff	0.0623	0.008	7.932	0.000	Toff	-0.0009	0.0009	-0.963	0.347
V	0.8648	0.265	3.260	0.004	V	-1.4356	0.6853	-2.095	0.049
Ip × Ip	0.4432	0.025	17.624	0.000	Ip × Ip	0.0426	0.0076	5.607	0.000
Ip × Ton	0.0340	0.003	10.090	0.000	V × V	0.0186	0.0076	2.450	0.024
Ip × Toff	-0.0041	0.000	-9.834	0.000	Ip × Toff	0.0003	0.0001	3.281	0.004
Ton × Toff	-0.0004	0.0001	-4.738	0.000	Ip × V	-0.0381	0.0034	-11.248	0.000
Ton × V	-0.0082	0.003	-2.438	0.024					

S = 1.687 R^2 = 98.9% R^2(adj) = 98.5% S = 0.3383 R^2 = 98.3% R^2(adj) = 97.6%

Table 4: ANOVA for MRR and Ra

MRR (mm^3/min)						Ra (µm)					
Source	DF	Seq SS	Adj S	F	P	Source	DF	Seq SS	AdjMS	F	P
Regression	9	5324.37	591.59	207.87	0.000	Regression	8	134.81	16.85	147.27	0.000
Linear	4	3794.64	153.99	54.11	0.000	Linear	4	109.83	1.16	10.18	0.000
Square	1	883.97	883.96	310.59	0.000	Square	2	9.27	4.64	40.52	0.000
Interaction	4	645.76	161.44	56.72	0.000	Interaction	2	15.71	7.85	68.65	0.000
Residual Error	20	56.92	2.84			Residual Error	20	2.29	0.11		
Lack-of-Fit	15	52.22	3.48	3.70	0.078	Lack-of-Fit	16	1.66	0.104	0.67	0.752
Pure Error	5	4.70	0.94			Pure Error	4	0.63	0.156		
Total	29	5381.29				Total	29	137.48			

B. Model for surface roughness

The RSM based analysis has been done to establish the mathematical model through the development of mathematical relationship between response Ra and the important process parameters, Based on the roughness test results obtained from the planned experiments, as shown in Table 2, the values of the different constants of the Eq. (1) are obtained for surface roughness model. The mathematical relationship for correlating the roughness, i.e., Ra phenomenon and the considered machining parameters has been established as follows:

$$Y_{(Ra)} = 32.8147 + 1.0465\,\text{Ip} + 0.0117\text{Ton} - 0.00009\,\text{Toff} - 1.4356\,\text{V} + 0.0426\,\text{Ip}^2 + 0.0186\,\text{V}^2 + 0.0003\,\text{Ip} \times Toff - 0.0381 Ip \times V \quad (5)$$

This mathematical model has been obtained to reflect the independent, quadratic and interactive effects of the various machining parameters on the machined Ra in EDM process.

The normal probability plot of residuals for MRR and Ra are illustrated in Figs. 1 and 2. It is expected that data from industrial experiments from a normal distribution. It reveals that the residuals fall on a straight line, implying that the errors are spread in a normal distribution. Here a residual means difference in the observed value (obtained from the experiment) and the predicted value or fitted value. The comparative results between the experimental values and the response surface model values are presented in Figures 3 and 4. It could be noted that closer the value to the line, more is the accuracy. In both the graphs the values very near to the line, this conform the adequacy of the model. This is also, conform by the variations between the experimental results and model predicted values are analyzed through residual graphs, and are presented in Figures 5 and 6. Figures reveal that there is no obvious pattern and unusual structure. This implies that the model proposed is adequate. Residual is the difference between the experimental values and model fitted values. From the analysis of the residual graphs, it can be established that there is no irregular variation between the experimental values and predicted values, and hence the developed model is highly significant and can be used for the prediction.

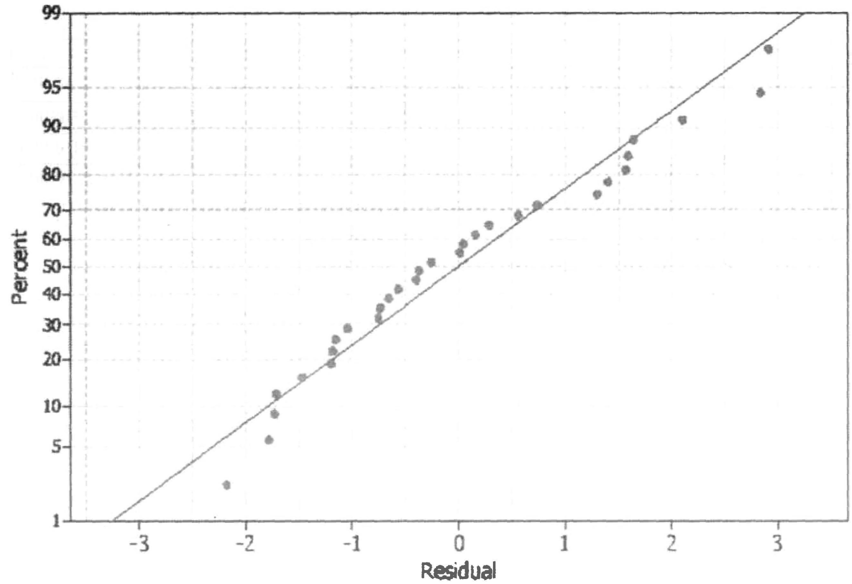


Figure 1: Normal Probability Plot of Residuals for MRR

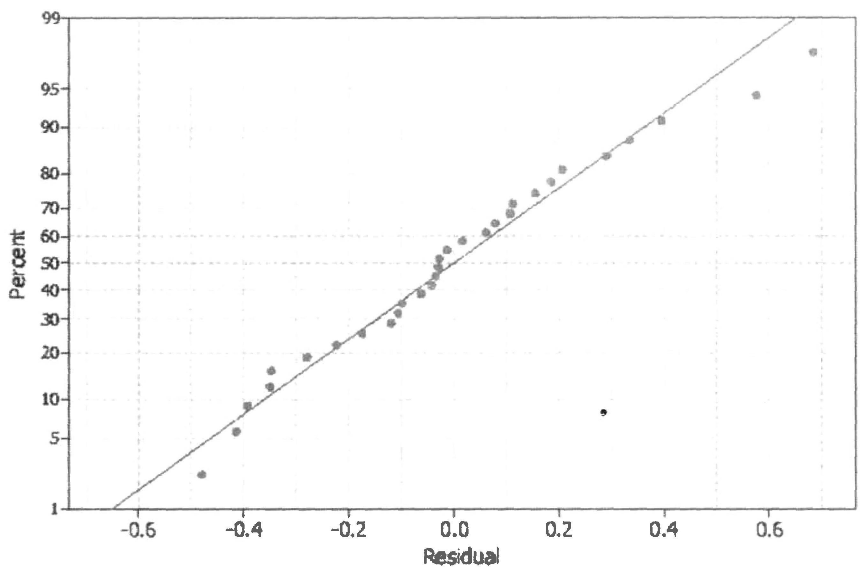


Figure 2: Normal Probability Plot of Residuals for Ra

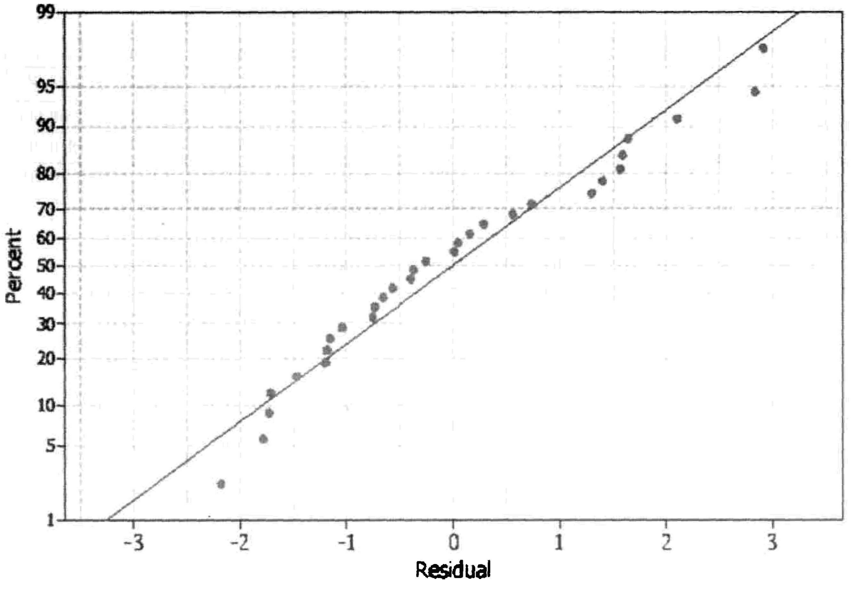


Figure 1: Normal Probability Plot of Residuals for MRR

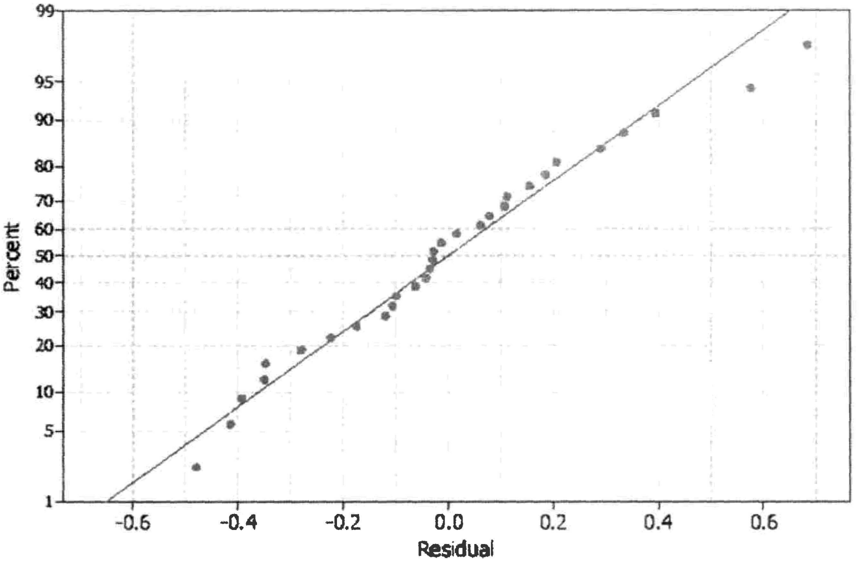


Figure 2: Normal Probability Plot of Residuals for Ra

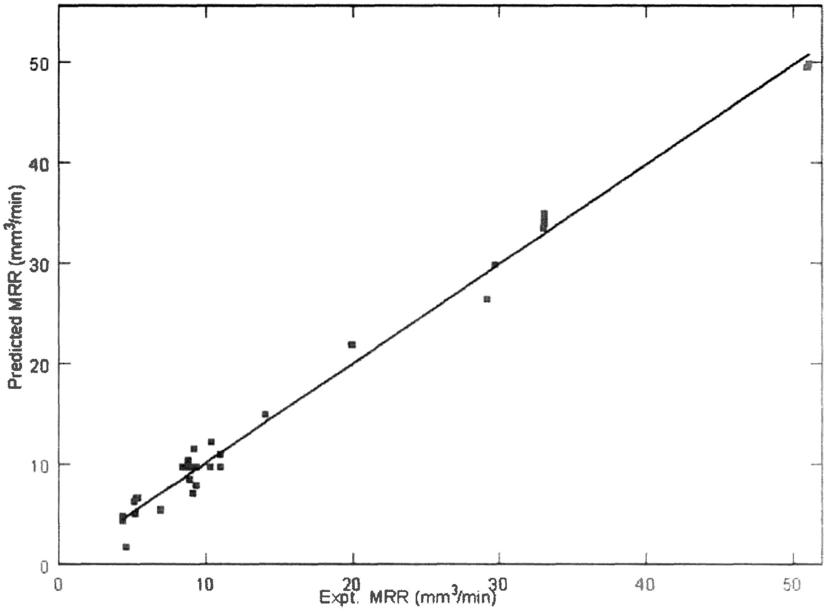


Figure 3: Plot of Expt. vs. Predicted Response of MRR

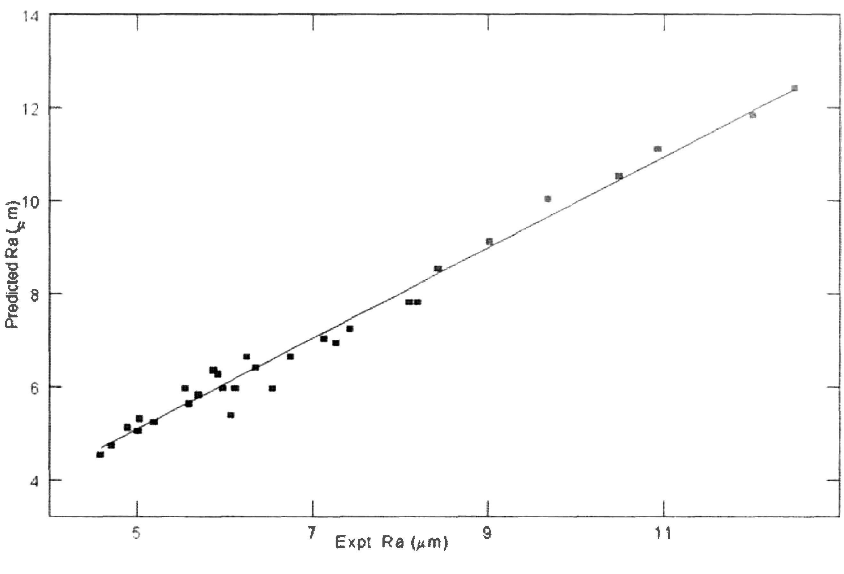


Figure 4: Plot of Expt. vs. Predicted Response of Ra

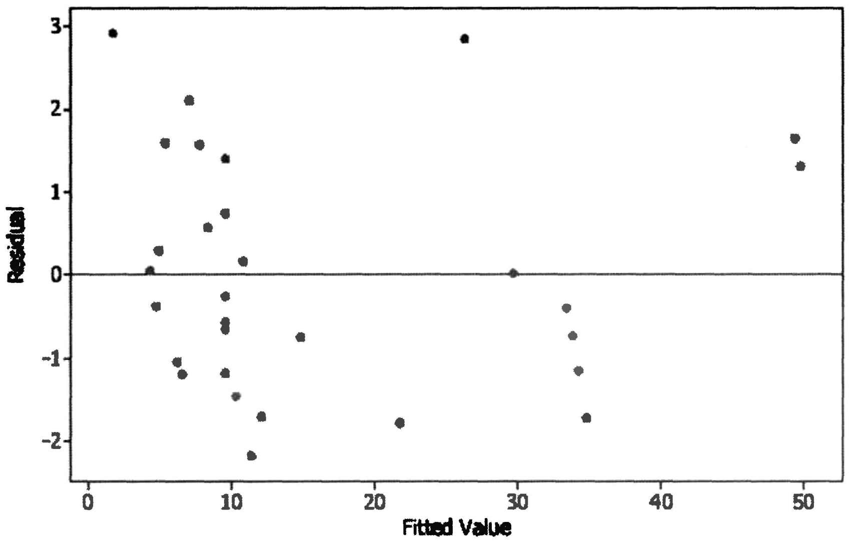


Figure 5: Plot of Residuals vs. Fits (MRR)

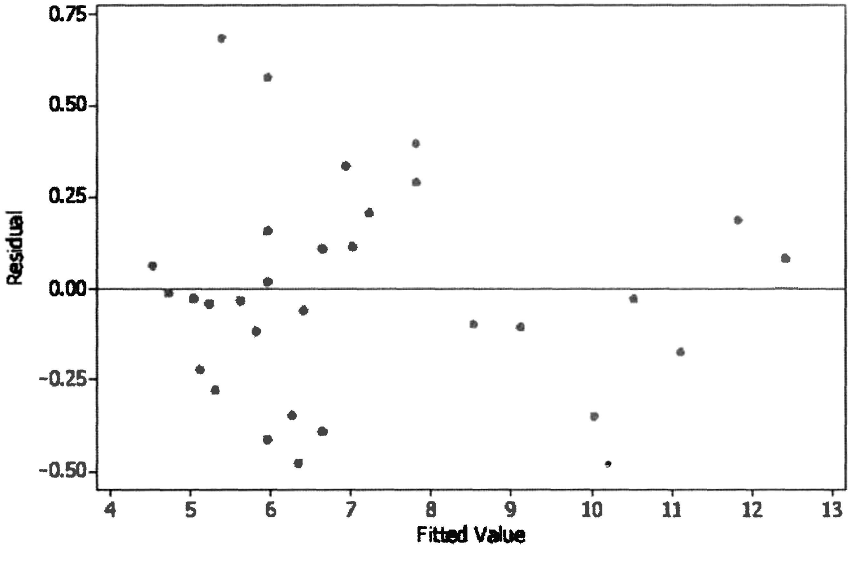


Figure 6: Plot of Residuals vs. Fits (Ra)

Results and Discussion

The parametric analysis has been carried out to study the influences of the input process parameters such as Ip, Ton, Toff and V on the process responses, such as MRR and Ra during EDM die-sinking process. Contour plots and three-dimensional response surface plots were formed based on the RSM quadratic models to evaluate the change of response surface. These plots can also give further assessment of the correlation between the input process parameters and responses.

Results and Analysis of the Material Removal Rate (MRR)

Figure 7(a), (b) illustrates the contour plot and response surfaces plot of MRR with respect to input parameters Ip and Ton. The value of MRR is shown to increase with an increase of Ip and Ton. This increase becomes more prominent as the value of Ip rises, due to the higher spark energy that produces the higher temperature cause more material to melt and erode from the workpiece. However, the gradient is more at the higher side of Ip and Ton than that of lower side.

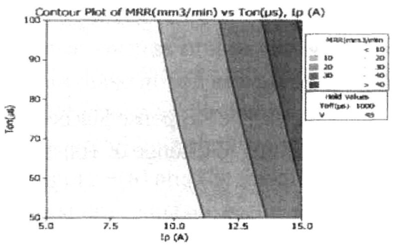


Figure 7(a): Contour Plot of MRR According to Change of Ip and Ton

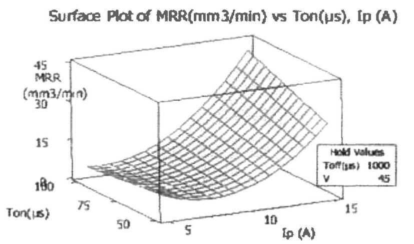


Figure 7(b): The Response Surface of MRR According to Change of Ip and Ton

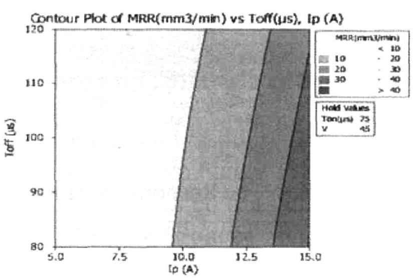


Figure 8(a): Contour Plot of MRR According to Change of Ip and Toff

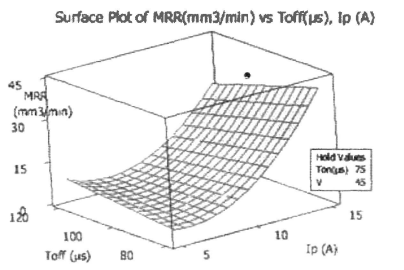


Figure 8(b): The Response Surface of MRR According to Change of Ip and Toff

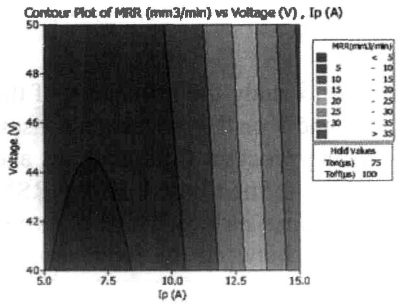


Figure 9(a): Contour Plot of MRR According to Change of Ip and V

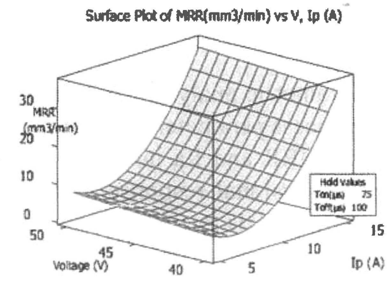


Figure 9(b): The Response Surface of MRR According to Change of Ip and V

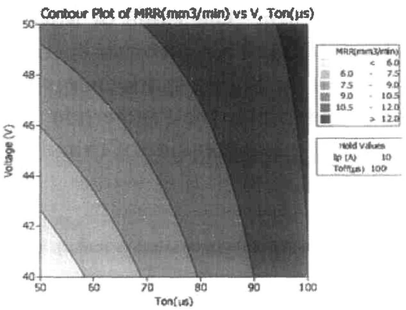


Figure 10(a): Contour Plot of MRR According to Change of Ton and V

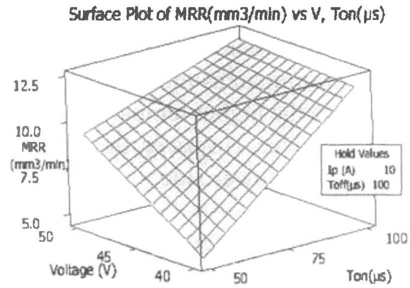


Figure 10(b): The Response Surface of MRR According to Change of Ton and V

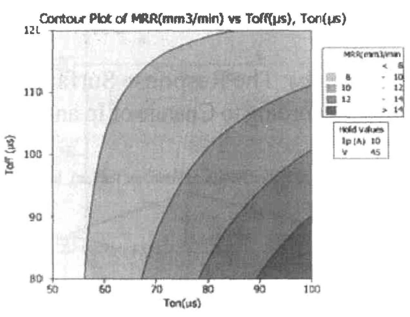


Figure 11(a): Contour Plot of MRR According to Change of Ton and Toff

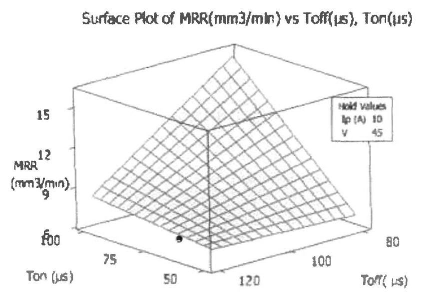
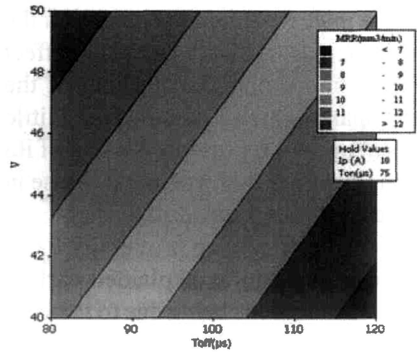


Figure 11(b): The Response Surface of **Mrr** According to Change of Ton and Toff



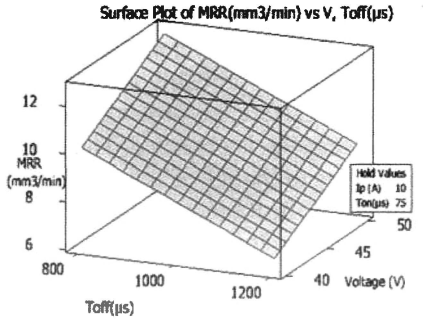


Figure 12(a): Contour Plot of MRR According to Change of Toff and V

Figure 12(b): The Response Surface of MRR According to Change of Toff and V

In the Figure 8(a), (b) contour plot and response surface of MRR with Ip and Toff is depicted. MRR increases with increase in Ip, and decreases with increase in Toff, because machining does not take place during the pulse-off time and it only adds to the non-cutting time. Due to this there will be an undesirable heat loss that does not contribute to MRR. This will lead to drop in the temperature of the workpiece before the next spark starts and therefore MRR The effect of Ton and Voltage on MRR is illustrated as contour and response surface plot in Figure 9(a) and (b), the response MRR is increases with increase in Ton as well as V. the reason being same as described above i.e. any increase in applied voltage increases the Ip, strong spark energy is created, and thus high temperature created by V and Ton leads to increase in MRR. In the Figure 9(a) and (b) the effect of Ip and V is depicted in the form of Contour and response surface respectively, which depicts that there is a sharp increase of MRR with Ip, however no appreciable increase in MRR with the increase in V. The contour and response surface plot of Ton and Toff is presented in Figure 11(a) and (b) and Toff and voltage in Figure 12(a) and (b) respectively. MRR is increasing with increase in Ton, V and decrease in Toff as stated earlier.

Results and Analysis of the Surface Roughness

The Contour and response surface graphs for the Ra are shown in Figures 13-18. It is clear from Figure 13(a), (b) that Ra increases with increase Ip and Ton. Spark energy, which is a function of Ip, Ton and V, increases with Ip and Ton which leads to produce higher crater volumes and hence the value of Ra is high. Figure 14(a), (b) represents the contour and response surface plot of Ra according to change in Ip and Toff. Since spark energy is proportional to Ip, hence with the increase in Ip Ra increases and there is no appreciable change in Ra, rather almost constant due to increase in Toff. This is because with the increase in Toff, only non machining time is increasing and it should not affect the roughness, probably during this there is more time for flushing of the debris, therefore, no obstacle for the next spark, which leads to a very little increase in Ra, is observed. The Figure 15(a) and (b) represents the plot of Ra according to change of Ton and Toff, which illustrates that with the increase in Ton and Toff, Ra increases due the same reason stated earlier

The effect of Ip and V on Ra is presented in the Figure 16 (a) and (b). It can be noted that the Ra is increasing with increase in Ip as explained earlier, however, the Ra decreases with increase in V. The reasons being due to increase in V, spark energy increases and due to this, larger but shallower craters are formed at higher voltage values due to expansion of the plasma channel in the discharge gap [16]. Figure 17 (a) and (b) and Figure 18 (a) and (b), explains the effect of Toff and voltage and Ton and V on Ra, respectively. It can be observed that with the increase in voltage and decrease in Toff and Ton, Ra decreases. The reason is explained earlier.

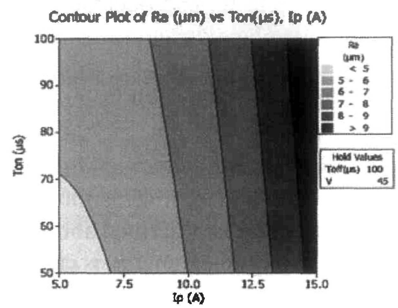


Figure 13(a): Contour Plot of Ra According to Change of Ip and Ton

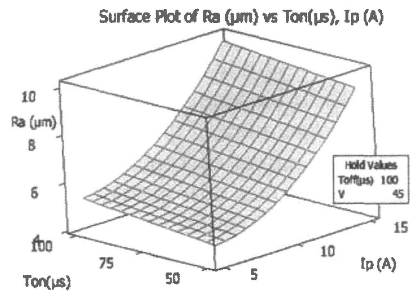


Figure 13(b): The Response Surface of Ra According to Change of Ip and Ton

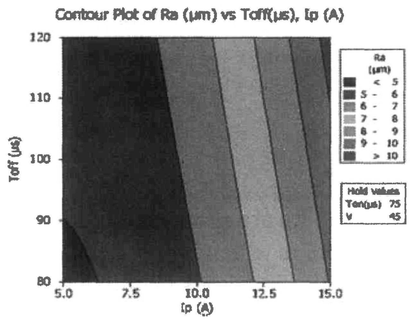


Figure 14(a): Contour Plot of Ra According to Change of Ip and Toff

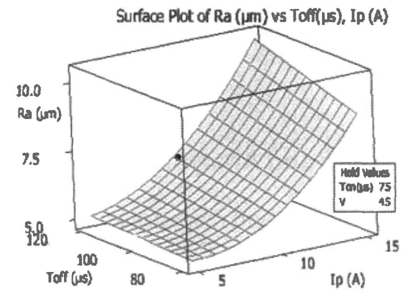
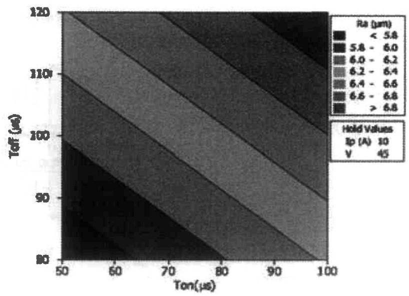


Figure 14(b): The Response Surface of Ra According to Change of Ip and Toff



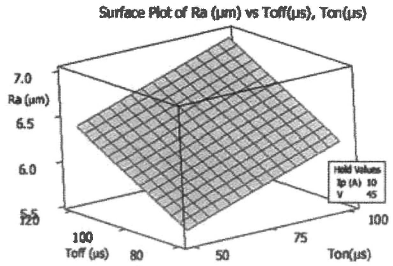
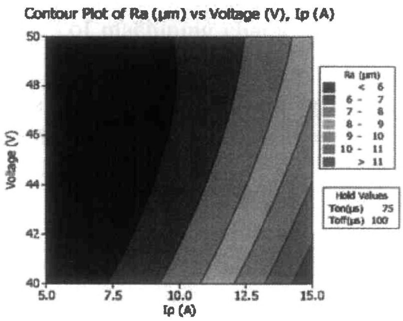


Figure 15(a): Contour Plot of Ra According to Change of Ton and Toff

Figure 15(b): The Response Surface of Ra According to Change of Ton and Toff



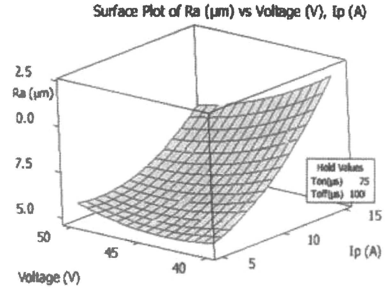
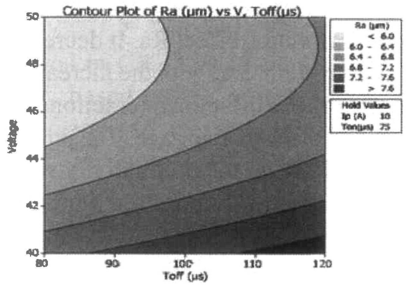


Figure 16(a): Contour Plot of Ra According to Change of Ip and V

Figure 16(b): The Response Surface of Ra According to Change of Ip and V



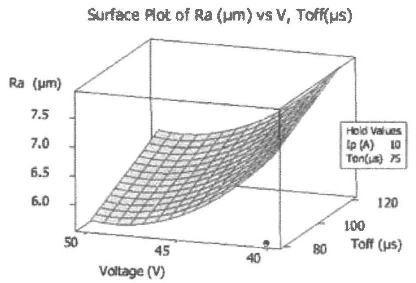


Figure 17(a): Contour Plot of Ra According to Change of Toff and V

Figure 17(b): The Response Surface of Ra According to Change of Toff and V

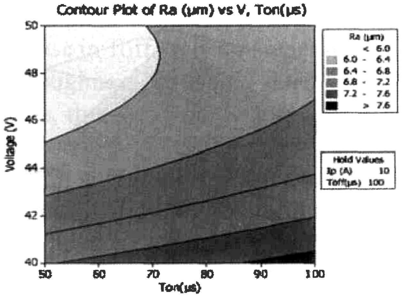


Figure 18(a): Contour Plot of Ra According to Change of Ton and V

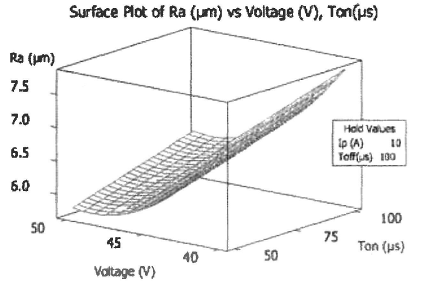


Figure 18(b): The Response Surface of Ra According to Change of Ton and V

Conclusions

Experimental investigation on electrical discharge machining of AISI D2 steel has been carried out with a view to correlate the process parameters with the responses such as MRR and surface roughness. The process has been successfully modeled using RSM and model adequacy checking was also carried out using Minitab (statistical software package). From the central composite design matrix, it is observed that for MRR the pulse current, pause time, voltage and pulse on time are significant factors. MRR increases with the increase in discharge current, pulse duration, and discharge voltage. However, it decreases with increase in pause time. For MRR, the most significant two-factor interaction effects are presented among pulse current and pulse on time, pulse current and off time, pulse on time and off time and pulse-on time and discharge voltage. It is also observed that discharge current, pulse duration and discharge voltage are the significant factors which effect Ra. It decreases with the decrease in discharge current, pulse duration, and with the increase in discharge voltage. However, the most significant two-factor interactions are pulse current and off time, and pulse current and discharge voltage. The present research approach is extremely useful for maximizing the productivity while maintaining surface finish and geometrical accuracy within desired limit. The developed technology setting in the field of electrical discharge machining of AISI D2 steel will find tremendous potentiality in modern industrial applications for efficient manufacturing of precision jobs. Besides the proposed modeling technique can also be utilized for advanced and conventional machining of other engineering materials in modern manufacturing industries.

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