Modeling and Analysis of process parameters on Surface Roughness in EDM of AISI D2 tool Steel by RSM Approach

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Abstract—In this research, Response Surface Methodology (RSM) is used to investigate the effect of four controllable input variables namely: discharge current, pulse duration, pulse off time and applied voltage Surface Roughness (SR) of on Electrical Discharge Machined surface. To study the proposed second-order polynomial model for SR, a Central Composite Design (CCD) is used to estimation the model coefficients of the four input factors, which are alleged to influence the SR in Electrical Discharge Machining (EDM) process. Experiments were conducted on AISI D2 tool steel with copper electrode. The response is modeled using RSM on experimental data. The significant coefficients are obtained by performing Analysis of Variance (ANOVA) at 5% level of significance. It is found that discharge current, pulse duration, and pulse off time and few of their interactions have significant effect on the SR. The model sufficiency is very satisfactory as the Coefficient of Determination (R^2) is found to be 91.7% and adjusted R^2-statistic (R^2_{adj}) 89.6%.

Keywords—Electrical discharge machining; Surface Roughness; Response Surface Methodology; ANOVA, Central composite design

I. Introduction

THough there has been tremendous progress over the decades in the field of materials science and engineering, innovation of new technologies, and need for better performances of existing technologies demands much more from the materials field. These materials are either traditional materials with enhanced properties or newly developed materials with high-performance capabilities. Today's manufacturing industry is facing challenges from these advanced and modern 'difficult-to-machine' materials, stringent design requirements (high precision, complex shapes and high surface quality) and very high machining cost. These materials play a progressively more vital role in modern manufacturing industries, especially in aircraft automobile, tool, die, and mould making industries. The improved thermal, chemical, and mechanical properties of the material have yielded enormous economic benefit to the manufacturing industries through improved product performance and product design. Tradition machining processes are not so efficient and are unable to machine the materials economically therefore they are increasingly being replaced by advance machining process, which make use of different class of energy for material removal using the material properties, like electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. EDM is an important machining process, extensively and effectively applied for the machining of such materials, precisely and cost-effectively in the said advance industry [1]. EDM is a process of machining electrically conductive materials by using preciously controlled sparks that occurs between an electrode and a work piece in presence of a dielectric fluid [2]. EDM is an well established technique used in modern manufacturing industry to produce high-precision machining of all types of conductive materials, alloy's and even ceramic materials, of any hardness and shape, which would have been difficult to manufacture by conventional machining. It is assertion that EDM is now the fourth most popular machining method after milling, turning, and grinding. However, the efficiency of machining is less in comparison to conventional machining Performance of any process is characterized by its product quality and productivity. The quality of any product significantly important in evaluating the productivity, and have considerable influence on the properties of the material such as wear resistant and fatigue strength. SR is expressed as the irregularities of material resulted from various machining operations. It is quoted as 'Ra' symbol and used to be called average roughness. Theoretically, Ra is the arithmetic average value of the departure of the profile from the mean line throughout the sampling length [3]. EDM process is very demanding but the mechanism of process is complex and far from completely understood. Therefore, it is hard to establish a model that can accurately predict the response (productivity, surface quality etc) by correlating the process parameter, though several attempts have been made. The important concern is the optimization of the process parameters such as pulse current intensity (Ip), pulse duration (Ton), pulse off time (Toff) and open circuit voltage (V) for minimize Surface roughness and the tool wear and simultaneously improving MRR.

Many attempts had been made for modelling of EDM process and investigation of the process performance to improve the surface quality and MRR are still challenging problems, which restrict the expanded application of the technology [4]. Pradhan and Biswas [5] presented a neuro-fuzzy model to predict MRR of AISI D2 tool steel with Ip, Ton and duty cycle (τ) as process parameter. The model predictions were found to be in good agreement with the experimental results. Pradhan et el. [6] also proposed two neural network models for the prediction of SR with the same input parameter and

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warkpiece material and compared the with the experimental results. It is claimed that the said models could predict SR successfully. Kanagarajan et al. [7] had chosen Ip, Ton, electrode rotation, and flushing pressure as design factor to study the EDM process performance such as SR and MRR on Tungsten carbide/cobalt cemented carbide. The most influential parameters for minimizing the SR have been identified using the RSM and experimentally verified by conducting confirmation experiments. Jaharah et al. [8] investigated the machining performance such as SR, electrode wear rate and MRR with copper electrode and AISI H3 tool steel workpiece and the input parameters taken are Ip, Ton, and Toff. The optimum condition for Ra was obtained at low Ip, low Ton, and Toff and concluded that the Ip was the major factor effecting both the responses, MRR and Ra.

The prime advantage of employing RSM is the reduced number of experimental runs required to generate sufficient information for a statistically adequate result. Many researches have applied RSM successfully to manufacturing environments. Kuppan at el. [9] derived mathematical model for MRR and average Ra of deep hole drilling of Inconel 718. The experiments were planned using CCD and RSM was used to model the same. It revealed that MRR is more influenced by peak current and duty factor, and the parameters were optimized for maximum MRR with the desired Ra value using desirability function approach. Chiang [10] had explained the influences of Ip, Ton, τ and voltage on the responses; MRR, electrodes wear ratio, and Ra. The experiments were planned according to a CCD and the influence of parameters and their interactions were investigated using ANOVA. A mathematical model was developed and claimed to fit and predict MRR accurately with a 95% confidence. Results show that the main two significant factors affecting the response are the Ip and the τ. Puertas at el. [11] analyzed the impact of EDM parameters on surface quality, MRR and electrode wear in cobalt-bonded tungsten carbide workpiece. A quadratic model was developed for each of the responses, and it was reported that for MRR, the current intensity factor was the most influential, followed by τ, Ton and the interaction effect of the first two. The value of MRR increased, when intensity and τ were increased, decreased with Ton. For the prediction of surface roughness empirical models and multi regression models are applied. [12], [13], [14] the interest is, however, the correlation of the surface parameters with the machining conditions and optimizes the EDM process. Erzurumlu at el. [3] have developed a RSM model and compared with the artificial neural network model. Pradhan and Biswas [15] however applied RSM model to estimate the influence of process parameters on material removal rate.

From the above researches, it can be seen that very few works has been report yet relating to modelling of SR of D2 steel in EDM using RSM. CCD and RSM were used to design the experiments the combined use of these techniques has allowed us to create models, which make it possible to explain the variability associated with each of the technological variables studied in this work. The aim of this study is to investigate the surface roughness of EDMed parts and explores possible ways to adjust its parameters to achieve better SR by statistical methods. The experiments are employed in this study to consider the effects of the Ip, Ton, Toff and discharge voltage (V) on surface roundness.

II. EXPERIMENTAL SET-UP

A number of experiments were conducted to study the effects of various machining parameters on EDM process. These studies were undertaken to investigate the effects of Ip, Ton, and on surface roughness. Where, the duty cycle is the ratio of Ton to sum of Ton and spark off time (Toff) in percentage. The selected workpiece material for the research work is AISI D2 (DIN 1.2379) tool steel. D2 steel was selected due to its emergent range of applications in the field of manufacturing tools in mould industries. Experiments were conducted on Electronica Electraplus PS 50ZNC die sinking machine. An electrolytic pure copper with a diameter of 30 mm was used as a tool electrode (positive polarity) and workpiece materials used were steel square plates of dimensions $15 \times 15mm^2$ and of thickness 4 mm. Commercial grade EDM oil (specific gravity = 0.763, freezing point = 94^0C) was used as dielectric fluid. Lateral flushing with a pressure of 0.3 kgf/cm^2 was used. The test conditions are depicted in TableI.

A. SURFACE ROUGHNESS MEASUREMENTS

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 1mm/second and 4 mm evaluation length. Roughness measurements, in the transverse direction, on the workpieces were repeated four times and average of four measurements of SR 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. SR is an important parameter in the EDM process. The parameters that affect 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

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

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' SR measurements of electro-discharge machined surfaces were taken to provide quantitative evaluation of the effect of EDM parameters on surface finish

III. RESPONSE SURFACE METHODOLOGY

RSM is a collection of mathematical and statistical techniques that are useful for modelling and analysis of problems in which output or response is influenced by several input variables and the objective is to find the correlation between the response and the variables investigated [16]. It is one of

the Design of Experiments (DOE) methods used to approximate an unknown function for which only a few values are computed. These relations are then modelled by using least square error fitting of the response surface. A Central Composite Design (CCD) is used since it gives a comparatively accurate prediction of all response variable averages related to quantities measured during experimentation [17]. CCD offers the advantage that certain level adjustments are acceptable and can be applied in the two-step chronological RSM. In these methods, there is a possibility that the experiments will stop with few runs and decide that the prediction model is satisfactory.

In CCD, the limits of the experimental domain to be explored are defined and are made as wide as possible to obtain a clear response from the model. The Ip, Ton, Toff and V are the machining variables selected for this investigation. The different levels taken for this study are depicted in Table I. The arrangement to conduct the experiments using a CCD with four variables, the cardinal points used are sixteen cube points, eight axial points and six centre point, in total of 30 runs in two blocks [18]. Machining was carried out for 15 min for each experiment, three replications of surface roughness measurement are taken, and in the design matrix, the average value of Ra is shown in Table II.

The second-order model is normally used when the response function is not known or nonlinear. In the present study, a second-order model has been utilized. The experimental values are analyzed and the mathematical model is then developed that illustrate the relationship between the process variable and response. The second-order model in equation 2 explains the behavior of the system.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i i X_i^2 + \sum_{i,j=1, i \neq j}^{k} \beta_{ij} X_i X_j + \epsilon \quad (2)$$

Where Y is the corresponding response, X_i is the input variables, $X_i^2 i$ and $X_i X_j$ 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.

TABLE I
DIFFERENT VARIABLES USED IN THE EXPERIMENT AND THEIR LEVELS.

Variable	Code	levels		
		1	2	3
Discharge current (Ip) in A	A	15	20	25
Pulse on time (Ton) in μs	B	25	50	75
Pulse off Time (Toff) in μs	C	50	75	100
Discharge Voltage (V) in volt	D	40	45	50

A. Regression models

Based on the experimental data gathered, statistical regression analysis enabled to study the correlation of process parameters with the MRR. Both linear and non-linear regression models were examined; acceptance was based on high to very high coefficients of correlation (r) calculated. In this study, for three variables under consideration, a polynomial regression is used for modeling. For simplicity, a quadratic model of MRR is proposed and can be written as shown in Equation **??**. The coefficients of regression model can be estimated from the experimental results. The effects of these variables and the interaction between them were included in this analyses and the developed model is expressed as interaction equation:

TABLE II
PLANNING MATRIX OF THE EXPERIMENTS WITH THE OPTIMAL MODEL DATA.

Run	Pt Type	Blocks	Ip (A)	Ton (μs)	Toff (μs)	V (Volt)	Ra (μm)
1	-1	2	20	25	75	45	3.10
2	-1	2	20	50	50	45	3.30
3	-1	2	20	75	75	45	5.01
4	-1	2	20	50	100	45	4.46
5	-1	2	15	50	75	45	2.48
6	-1	2	25	50	75	45	3.92
7	-1	2	20	50	75	50	4.01
8	0	2	20	50	75	45	3.96
9	0	2	20	50	75	45	3.75
10	-1	2	20	50	75	40	3.62
11	0	1	20	50	75	45	3.85
12	1	1	15	75	50	40	2.72
13	1	1	15	75	50	50	1.96
14	0	1	20	50	75	45	3.69
15	1	1	25	25	50	50	3.59
16	1	1	25	25	50	40	2.81
17	1	1	15	75	100	50	3.15
18	1	1	25	75	100	40	5.74
19	1	1	15	25	100	50	2.11
20	1	1	25	75	50	50	4.65
21	1	1	25	75	100	50	5.42
22	1	1	15	25	50	40	2.46
23	1	1	15	25	50	50	2.66
24	0	1	20	50	75	45	4.12
25	1	1	15	75	100	40	2.63
26	1	1	25	25	100	40	3.42
27	1	1	15	25	100	40	1.91
28	1	1	25	75	50	40	4.99
29	1	1	25	25	100	50	2.64
30	0	1	20	50	75	45	4.41

The unknown coefficients are determined from the experimental data as presented in Table III. The standard errors on estimation of the coefficients are tabulated in the column 'SE coef'. The F ratios are calculated for 95% level of confidence and the factors having p-value more then 0.05 are considered insignificant (shown with ** in p-column). For the appropriate fitting of SR, the non-significant terms are eliminated by the backward elimination process. The regression model is re-evaluated by determining the unknown coefficients, which are tabulated in Table 4. The model made to represent SR depicts that Ip, Ton, Ip^2, and interaction of Ton and Toff are the most influencing parameters in order of significance. The final response equation for SR is given in equation 3.

Since, EDM process is non-linear in nature, a linear polynomial will be not able to predict the response accurately, and therefore the second-order model (quadratic model) is found

to be adequately model the process. The ANOVA table for the curtailed quadratic model (Table 5) depicts the value of Coefficient of determination R^2 as 92.1%, which signifies that how much variation in the response is explained by the model. The higher of R^2, indicates the better fitting of the model with the data. However, R^2_{adj} is 89.6%, which accounts for the number of predictors in the model describes the significance of the relationship. It is important to check the adequacy of the fitted model, because an incorrect or under-specified model can lead to misleading conclusions. By checking the fit of the model one can check whether the model is under specified. The model adequacy checking includes the test for significance of the regression model, model coefficients, and lack of fit, which is carried out subsequently using ANOVA on the curtailed model (Table. V). The total error on regression is sum of errors on linear, square, and interactions terms (26.7139 = 19.8984 + 2.6913 + 4.1241). The residual error is the sum of pure and lack-of-fit errors. The fit summary recommended that the quadratic model is statistically significant for analysis of SR. In the table, p-value for the lack-of-fit is 0.318, which is insignificant, so the model is certainly adequate. Moreover, the mean square error of pure error is less than that of lack-of-fit. The final model tested for variance analysis (F-test) indicates that the adequacy of the test is established. The computed values of response parameters, model graphs are generated for the further analysis in the next section.

$$\begin{aligned} Ra &= -5.76 + 0.97 \times Ip - 0.076 \times Ton - 0.015 \times Toff \\ &- -0.0013 \times V - 0.024 \times Ip^2 + 0.0035 \times Ip \times Ton \\ &+ 0.00041 \times Ton \times Toff \end{aligned} \tag{3}$$

TABLE III
ANOVA TABLE FOR SR (BEFORE ELIMINATION).

Term	Coef	SE Coef	t	p
Constant	-12.6644	18.1754	-0.697	0.497
Block	0.0652	0.0958	0.681	0.507
Ip (A)	1.0925	0.4199	2.602	0.021
Ton (μs)	-0.0438	0.0542	-0.808	0.433
Toff (μs)	-0.0264	0.0682	-0.387	0.705
V (Volt)	0.2352	0.8563	0.275	0.788
Ip $\times$Ip	-0.0263	0.0094	-2.783	0.015
Ton$\times$Ton	-0.0000	0.0004	-0.073	0.943 **
Toff$\times$Toff	0.0000	0.0004	0.096	0.925 **
V $\times$V	-0.0017	0.0094	-0.179	0.860 **
Ip $\times$ Ton	0.0035	0.0008	4.671	0.000
Ip $\times$ Toff	0.0006	0.0008	0.791	0.442 **
Ip $\times$ V	-0.0021	0.0038	-0.552	0.590 **
Ton $\times$ Toff	0.0004	0.0002	2.704	0.017
Ton $\times$ V	-0.0007	0.0008	-0.870	0.399 **
Toff $\times$V	-0.0001	0.0008	-0.179	0.860 **
S = 0.3762		$R^2 = 93.2\%$ $R^2_{(adj)} = 85.8\%$		

IV. RESULT AND DISCUSSION

The effect of the machining parameters (Ip, Ton Toff and V) on the response variables SR have been evaluated by conducting experiments as described the previous section and analysed using Minitab software [18]. ANOVA is used to check the sufficiency of the second-order model. SR obtained from the experiment is compared with the predicted value calculated from the model in Fig. 1. Since all the points on plot come close to form a straight line, it implies that the data are normal. It can be seen that the regression model is reasonably well fitted with the observed values. In addition, the plot of the residues verse predicted SR illustrates that there is no noticeable pattern or unusual structure present in the data as depicted in Fig 2. The residues, which are calculated as the difference between the predicted and observed value lies in the range of -0.51 to 0.494.

TABLE IV
ANOVA TABLE FOR SR (BEFORE ELIMINATION).

Term	Coef	SE Coef	t	p
Constant	-5.76514	2.17575	-2.650	0.015
Ip(A)	0.97036	0.19597	4.952	0.000*
Ton(μss)	-0.07605	0.01644	-4.625	0.000*
Toff(μs)	-0.01513	0.00715	-2.117	0.046
V(Volt)	-0.00133	0.01523	-0.088	0.931**
Ip$\times$Ip	-0.02446	0.00482	-5.077	0.000*
Ip$\times$Ton	0.00352	0.00065	5.439	0.000*
Ton$\times$Toff	0.00041	0.00013	3.149	0.005*
S = 0.3231		$R^2 = 92.1\%$ $R^2_{(adj)} = 89.6\%$		
*-Significant, **-Non-significant				

TABLE V
THE ANOVA TABLE FOR THE FITTED MODELS.

Source	DF	Seq. SS	Adj. MS	F	p
Regression	7	26.7139	3.81627	36.55	0.000
Linear	4	19.8984	1.39697	13.38	0.000
Square	1	2.6913	2.69133	25.77	0.000
Interaction	2	4.1241	2.06206	19.75	0.000
Residual Error	22	2.2973	0.10442		
Lack-of-Fit	17	1.9402	0.11413	1.60	0.318***
Pure Error	5	0.3571	0.07143		
Total	29	29.0112	***-Non Significant		

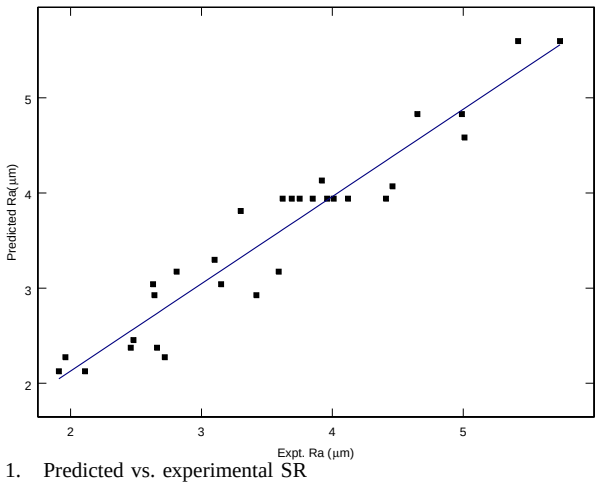

Fig. 1. Predicted vs. experimental SR

Fig 3 shows the estimated response surface for SR in

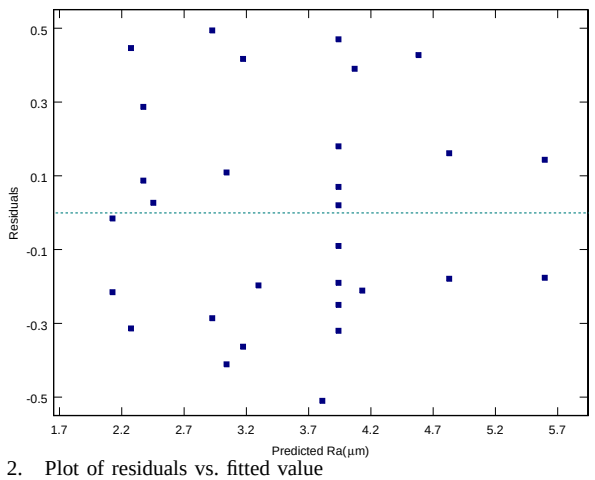

Fig. 2. Plot of residuals vs. fitted value

relation to the process parameters of Ip and Ton while Toff and V remain constant at their lowest value. It can be seen from the figure, the SR tends to increase significantly with the increase in Ip for any value of Ton. However, the SR tends to increase with increase in Ton, especially at higher Ip. Hence, minimum SR is obtained at low peak current (15 A) and low pulse on time (25μs). This is due to their dominant control over the input energy, i.e. with the increase in Ip generates strong spark, which create the higher temperature and crater, hence rough surface in the workpiece and low Ip creates small crater and therefore smooth surface.

The effect of Ip and Toff is on the estimated response surface of SR is depicted in Fig. 4, Ton and V remains constant in its lower level of 25μs and 40 volt, respectively. It can be noted that the SR increases when the Ip increases, the explanation is same, as stated earlier. However, with the increase in Toff, SR decreases. It is because there will be an undesirable heat loss at higher Toff, which leads to drop in the temperature of the workpiece before the next spark starts and therefore formation of crater size decreases.

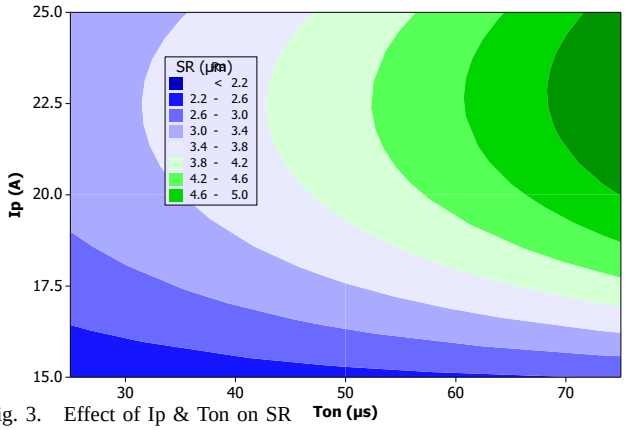

Fig. 3. Effect of Ip & Ton on SR

The smooth surface is achieved with low Ip = 15 A, lower Ton=25μs and higher Toff = 100 μs for the given range of input parameters. Fig. 5 represents SR as a function of Ton and Toff, whereas the Ip and V remains constant at its lower level. It is observed that the SR values are low when Ton is low with higher Toff or Toff is low with higher Ton. Similar inferences can be drawn from Table **??**, where the interaction of Ton and Toff is significant. Although the influence of this two parameter is very less when compared with the effect of Ip on SR. Finally, Fig. 6, Fig. 7, and Fig.8, represents the effect

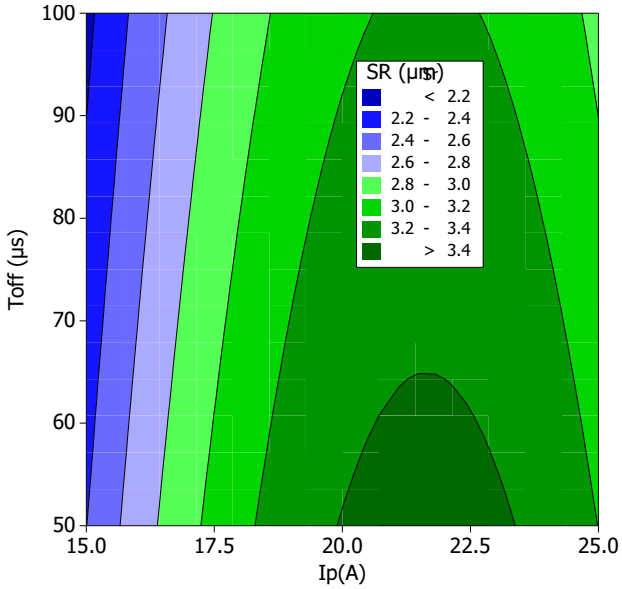

Fig. 4. Effect of Ip & Toff on SR

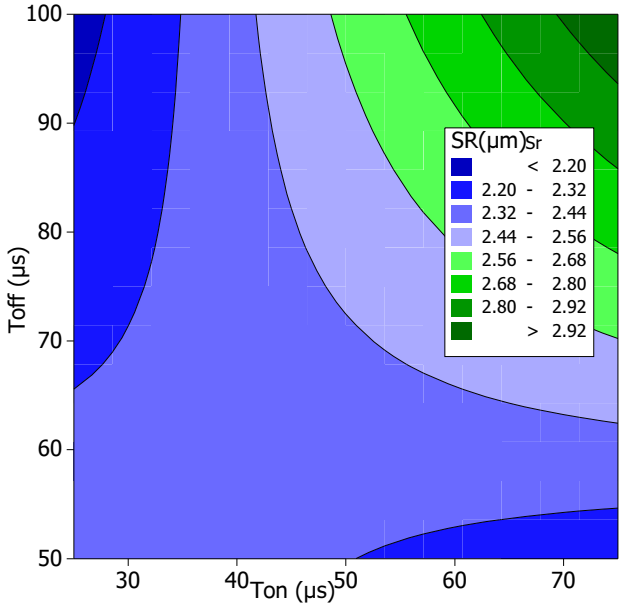

Fig. 5. Effect of Ton & Toff on SR

of voltage with other three parameters (Ip, Ton and Toff) on SR. It can be observed that there is no significant variation of SR with the variation of voltage. From this observation, it can be concluded that Ip and Ton are directly proportional, and Toff is inversely to the SR for the given range of experiments conducted for our test.

V. CONCLUSION

In the present study, the process parameters with significant influence on Surface roughness were determined by using RSM. A second order response model of these parameters are developed and found that pulse current, discharge time, and interaction term of pulse current with other parameters significantly affect the surface roughness. Surface roughness is directly proportional to linear effect of pulse current and pulse on time. The lower value of surface roughness is achieved with Ip = 15 A, Ton = 25 μs and Toff = 100 μs within the experimental domain. The research findings of the present study based on RSM models can be used effectively in machining of AISI D2 tool steel in order to obtain best possible EDM efficiency. This research can also help researches and

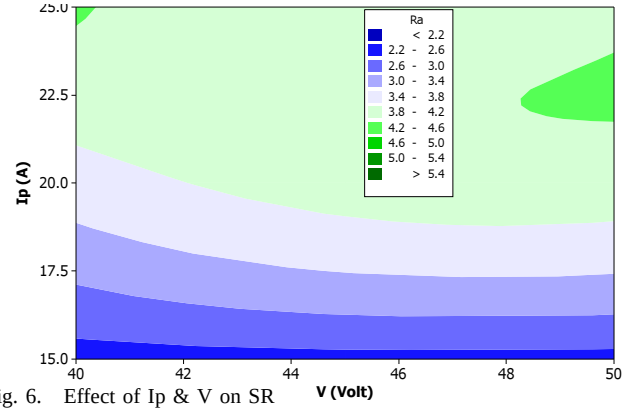

Fig. 6. Effect of Ip & V on SR

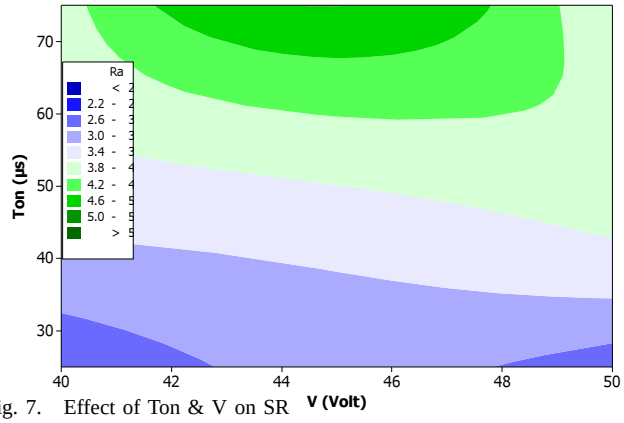

Fig. 7. Effect of Ton & V on SR

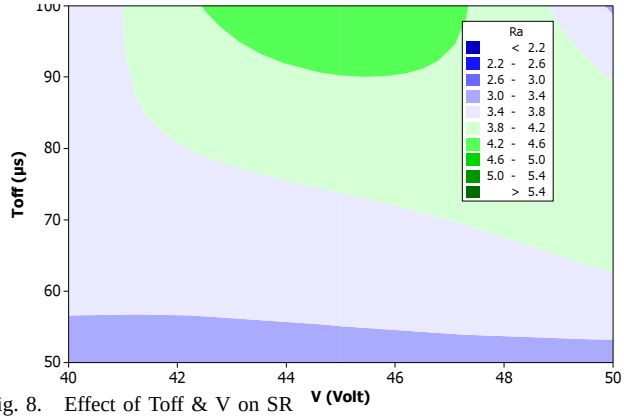

Fig. 8. Effect of Toff & V on SR

industries for developing a robust, reliable knowledge base and early prediction of surface roughness without experimenting with EDM process for AISI D2 tool.

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