Multi-Parameter Analysis and Modeling of Surface Roughness in Electro Discharge Machining of AISI D2 Steel

B B PATEL, K B RATHOD

Abstract— Whereas the efficiency of traditional cutting processes is limited by the mechanical properties of the processed material and the complexity of the workpiece geometry, electrical discharge machining (EDM) being a thermal erosion process, is subject to no such constraints. Surface roughness (Ra) is a significant upshot in the manufacturing process and it materializes a major part in the manufacturing system. It depends on different machining parameters and its prediction and control is a query to the researchers. This paper highlights 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 of surface roughness. The adequacies of the above proposed model have been tested through the analysis of variance (ANOVA).

Index Terms— Central composite design, EDM, Surface roughness, Response surface methodology.

1 INTRODUCTION

Electrical discharge machining (EDM) is a non-traditional manufacturing process based on removing material from a part by means of a series of repeated electrical discharges (created by electric pulse generators at short intervals) between a tool, called the electrode, and the part being machined in the presence of a dielectric fluid. At present, EDM is a widespread technique used in industry for high-precision machining of all types of conductive materials [1]. The working principle is based on the thermo electric energy. The thermo electric energy (in form of spark) is created between a workpiece and an electrode submerged in a dielectric fluid with conduction of electric current. The workpiece and the electrode are separated by a specific small gap, the so called ‘spark gap’, and pulsed discharges occur in this gap filled with an insulating medium [2]. During machining, the discharge energy produces very high temperature at the point of the spark on the surface of the workpiece, and removes the material by melting and vaporization. The top surface of workpiece resolidifies and cools subsequently at very high rate. This process leads to the slightly dimpled surface (i.e. increasing surface roughness), which facilitates crack initiation on the surface. After electrical discharge treatment, high tensile residual stresses often induce damage such as micro-cracks or pinholes in the surface layer, reducing its strength. Y.H. Guu et al. [3] proved that AISI D2 steel coated by TiN exhibited considerably increased hardness, a better surface finish, and decreased superficial tensile residual stress, or added compressive residual stress on the surface, increasing their fatigue limit. Y.H. Guu et al. [4] further studied the effect various machining parameters on SR of AISI D2 steel. Experimental results indicate that the thickness of the recast layer, and surface roughness are proportional to the power input. Y.H. Guu et al. [5] studied the three-dimensional images of AISI D2 tool steel machined by the EDM process was analyzed by means of the atomic force microscopy technique. The AFM study of the surface morphology of the EDM specimen has revealed that higher discharge energy results in a poorer surface structure. To avoid excessive machined damage, low discharge energy should be used. M. K. Pradhan and C. K. Biswas et al. [6, 7] developed regression model and two artificial neural networks (ANNs) namely: Back propagation and radial basis function to predict surface roughness in electrical discharge machined surfaces. S. Prabhu and B.K. Vinayagam et al. [8] used single-wall carbon nano tube mixed with dielectric fluids in EDM process to analysis the surface characteristics like surface roughness, micro cracks in AISI D2 tool steel a work piece material which is very much used in moulds and dies. An excellent machined nano finish can be obtained by setting the machine parameters at low pulse energy.

- *B B Patel is currently Assistant Professor in Sankalchand Patel college of Engineering, Visnagar, India, Email: bbpatel.mech@spcevng.ac.in*
- *K B Rathod currently Assistant Professor in Faculty of Engineering Technology and Research, Bardoli, India. E-mail: Rathod_kb@yahoo.co.in*

2 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 various machining parameters on surface roughness. The selected workpiece material for the research work is AISI D2 tool steel. D2 steel was selected due to its emergent range of applications in the field of manufacturing tools in mould industries. During the heat treatment, the material was heated to 1030 0C at a heating rate of 20 0C min-1. Then, the material was held at 1030 0C for 1 h and was quenched. After quenching, the specimens were tempered at 350 0C for 2 h and then air cooling. Experiments were conducted on JOEMARS Z 50 JM-322 die sinking machine using reverse polarity. The flushing pressure was 0.5 Kg/cm2. The copper with a diameter of 15 mm was used as a tool electrode and Die-electric fluid-92 (DEF-92) was used as die electric fluid. The test conditions are depicted in Table-1.

In present analysis surface roughness is measured on a mitutoyo make portable digital surface finish tester (model: surftest set no: 178-923e).

3 RESPONSE SURFACE METHODOLOGY

RSM is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which the response of interest is influenced by several variables and objective is to optimize this response [9]. The central composite rotatable design (CCRD) is useful than full factorial designs, since it requires much fewer tests and shown to be sufficient to describe the responses [10]. Thus, CCRD was chosen to determine the relationship between four operating variables namely, pulse current, pulse on-time, pulse off-time and spark gap voltage. In order to study the effects of the EDM parameters on the above mentioned machining criteria, second order polynomial response surface mathematical models can be developed. In the general case, the response surface is described by an equation of the form:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^{\,2} + \sum_{i<j=2}^{2} \beta_{ij} x_i x_j + \varepsilon_r$$

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 $\beta_0, \beta_{i,} \beta ij$ and β_{ii}.

In order to determine the equation of the response surface, experimental design has been developed with the attempt to approximate this equation using the smallest number of experiments possible. In this investigation, experimental design was established on the basis of 2k factorial, where k is the number of variables, with central composite-second-order rotatable design to improve the reliability of results and to reduce the size of experimentation without loss of accuracy. Thus, the minimum possible number of experiments (N) can be determined from the following equations:

$$N = n_c + n_a + n_{\dots},$$

$$n_c = 2^k$$

$$n_a = 2 \times k$$

Where nc parameter defines the number of factorial points or corner points. One central composite design consists of cube points at the corners of a unit cube that is the product of the intervals [-1, 1]. The na parameter defines the number of axial points or star points along the axes or outside the cube at a distance c = k1/2 from the centre point of the design to a star point and no parameter means the number of centre points at the origin and can be get from tables according to the number of independent variables [11].

In this case k = 4 and thus n_c = 2×k = 16 corner points at ±1 level, n_a = 2×k = 8 axial points at c = ±2, and a centre point at zero level repeated 7 times (no). This involves a total of 31 experimental observations. The coded levels for all process parameters used are shown in Table-1.

TABLE 1
CODING LEVELS OF PROCESS PARAMETERS

Level	Ip (amp)	Ton (µs)	Toff (µs)	V (volt)
+2	6	75	50	12
+1	9	80	55	13
0	13	85	60	14
-1	17	90	65	15
-2	21	95	70	16

TABLE 2
PLAN FOR CENTRAL COMPOSITE ROTATABLE SECOND-ORDER DESIGN

Sr. No	Ip (A)	Ton (μs)	Toff (μs)	V (volts)	Ra (μm)
1	17	90	65	15	6.873
2	9	90	65	15	5.167
3	17	80	65	15	5.949
4	9	80	65	15	5.626
5	17	90	55	15	6.784
6	9	90	55	15	5.184
7	17	80	55	15	4.662
8	9	80	55	15	4.694
9	17	90	65	13	8.399
10	9	90	65	13	6.675
11	17	80	65	13	5.902
12	9	80	65	13	4.879
13	17	90	55	13	6.917
14	9	90	55	13	5.131
15	17	80	55	13	5.445
16	9	80	55	13	5.339
17	21	85	60	14	6.620
18	6	85	60	14	4.623
19	13	95	60	14	7.088
20	13	75	60	14	5.367
21	13	85	70	14	6.47
22	13	85	50	14	6.422
23	13	85	60	16	6.148
24	13	85	60	12	6.132
25	13	85	60	14	5.503
26	13	85	60	14	5.503
27	13	85	60	14	5.503
28	13	85	60	14	5.503
29	13	85	60	14	5.503
30	13	85	60	14	5.503
31	13	85	60	14	5.503

The unknown coefficients are determined from the experimental data as presented in Table-3. 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. For improving the value of R2 the unusual observation with large standardized residual (i.e. 7, 8, 10, and 22) were eliminated. The regression model is reevaluated by determining the unknown coefficients, which are tabulated in Table-4. The final response equation for SR is given in below equation.

$$
\begin{aligned}
Ra &= 54.3206 - 1.5077\times Ip - 1.0036\times Ton \\
&- 1.2045\times Toff + 5.0810\times V \\
&+ 1.6E-03\times Ip\times Ip + 7.1E-03\times Ton\times Ton \\
&+ 8E-03\times Toff\times Toff + 1.557E-01\times V\times V \\
&+ 1.88E-02\times Ip\times Ton + 6E-03\times Ip\times Toff \\
&- 2.59E-02\times Ip\times V + 1.03E-02\times Ton\times Toff \\
&- 7.17E-02\times Ton\times V - 4.98E-02\times Toff\times V
\end{aligned}
$$

TABLE-3
ANOVA TABLE FOR SR BEFORE ELIMINATION

Term	Coef	SE Coef	T	P
Constant	70.713	52.6420	1.343	0.198
Ip	-1.3032	0.7036	-1.852	0.083
Ton	-0.7571	0.6957	-1.088	0.293
Toff	-0.9936	0.6300	-1.577	0.134
V	-0.0183	3.2718	-0.006	0.996
Ip×Ip	0.0008	0.0051	-0.161	0.874
Ton×Ton	0.0055	0.0033	1.679	0.113
Toff×Toff	0.0077	0.0033	2.342	0.032
V×V	0.1164	0.0824	1.413	0.177
Ip×Ton	0.0169	0.0055	3.063	0.007
Ip×Toff	0.0041	0.0055	0.747	0.466
Ip×V	-0.0163	0.0275	-0.591	0.562
Ton×Toff	0.0022	0.0044	0.501	0.623
Ton×V	-0.0310	0.0220	-1.408	0.178
Toff×V	-0.0092	0.0220	-0.415	0.683
R2 = 85.51 %, R2(adj) = 72.84%				

The ANOVA table for the curtailed quadratic model (Table-4) depicts the value of Coefficient of determination R2 as 98.38%, which signifies that how much variation in the response is explained by the model. The higher of R2, indicates the better fitting of the model with the data. However, R2 adj is 96.49%, which accounts for the number of predictors in the model describes the significance.

TABLE 4

ANOVA TABLE FOR SR AFTER ELIMINATION

Term	Coef	SE Coef	T	P
Constant	54.3206	19.1554	2.836	0.015
Ip	-1.5077	0.2763	-5.457	0.000
Ton	-1.0036	0.2467	-4.069	0.002
Toff	-1.2045	0.2846	-4.232	0.001
V	5.0810	1.6194	3.137	0.009
Ip×Ip	0.0016	0.0019	0.876	0.398
Ton×Ton	0.0071	0.0012	5.964	0.000
Toff×Toff	0.0080	0.0018	4.519	0.001
V×V	0.1557	0.0298	5.229	0.000
Ip×Ton	0.0188	0.0026	7.239	0.000
Ip×Toff	0.0060	0.0026	2.327	0.038
Ip×V	-0.0259	0.0130	-1.997	0.069
Ton×Toff	0.0103	0.0024	4.314	0.001
Ton×V	-0.0717	0.0120	-5.981	0.000
Toff×V	-0.0498	0.0120	-4.158	0.001

R2 = 98.38% R2(adj) = 96.49%

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-5).

TABLE 5

ANOVA TABLE FOR THE FITTED MODEL

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	17.3722	17.372	1.2408	52.02	0.00
Linear	4	12.6305	1.8268	0.4567	19.15	0.00
Square	4	1.2831	1.7166	0.4291	17.99	0.00
Interaction	6	3.4585	3.4585	0.5764	24.17	0.00
Residual Error	12	0.2862	0.2862	0.0238		
Lack-of-Fit	6	0.2862	0.2862	0.0477		
Pure Error	6	0.0000	0.0000	0.0000		
Total	26	17.6584				

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 analyzed using Minitab software. 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.

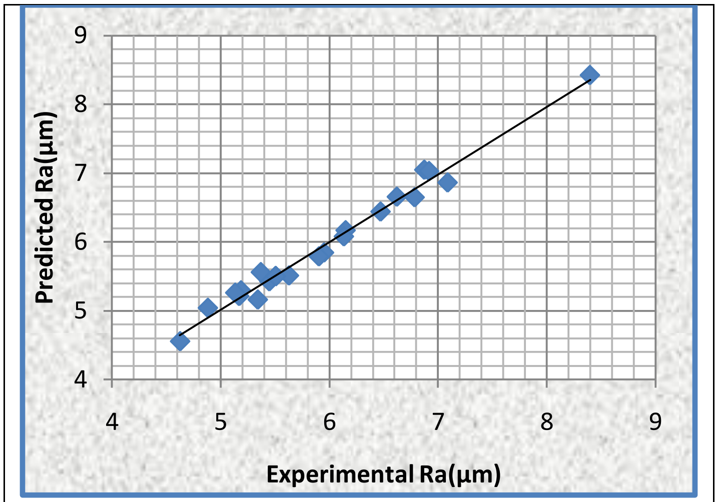

Fig.1. Predicted vs. experimental SR

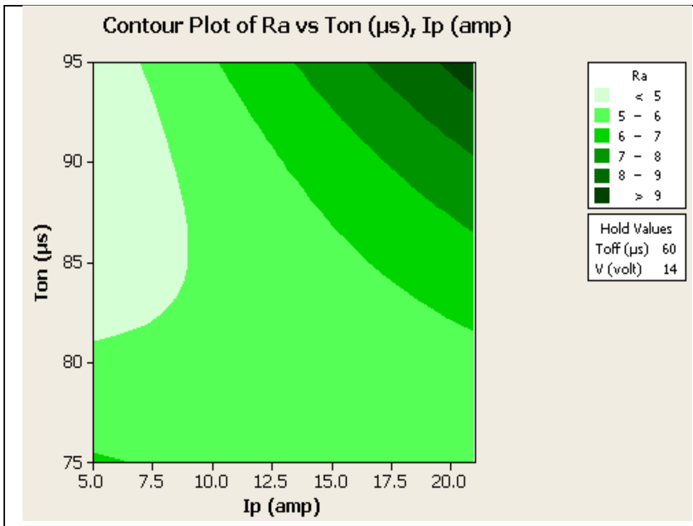

Fig. 2. Effect of Ip & Ton on SR

Fig. 2 shows the estimated response surface for Surface Roughness in relation to the process parameters of Ip and Ton while Toff and V remain constant at their middle 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 and low pulse on time. This is due to their dominant control over the input energy, i.e. with the increase in Ip and Ton generates strong spark for longer time, which create the higher temperature and crater, hence rough surface in the workpiece and low Ip creates small crater and therefore smooth surface.

Fig. 3 shows the estimated response surface for Surface Roughness in relation to the process parameters of Ip and Toff while Ton and V remain constant at their middle value. It can be seen from the figure, the SR tends to increase significantly with the increase in Ip, the explanation is same, as stated earlier. However, with the increase in Toff, SR decreases. It is because it takes time before next spark and reduces the crater effect due to higher temperature.

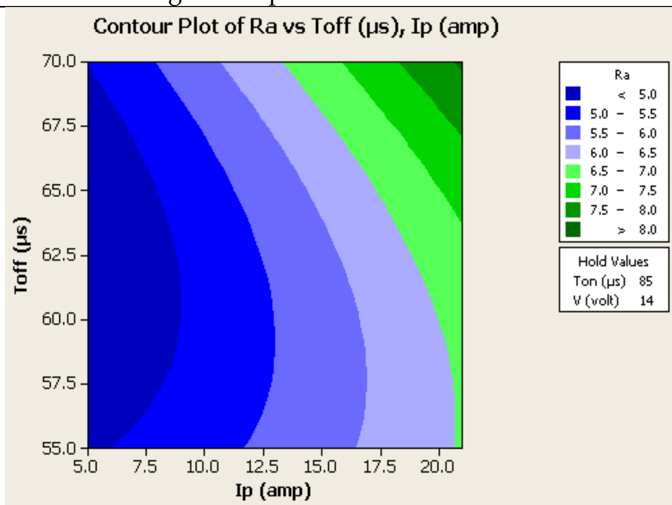

Fig. 3. Effect of Ip & Toff on SR

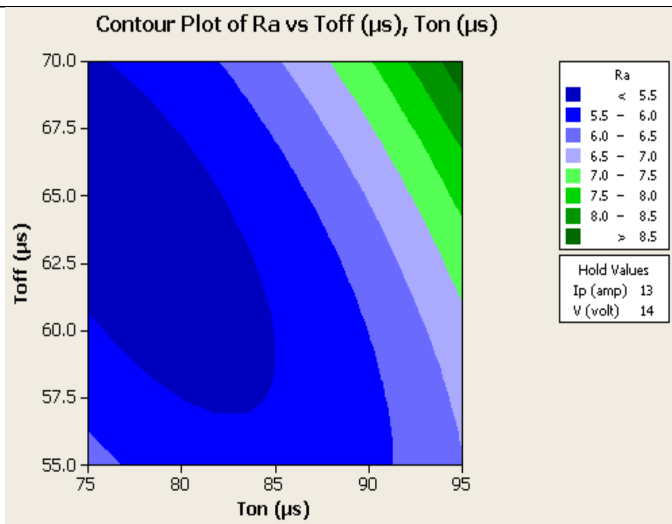

Fig. 4. Effect of Ip & V on SR

Fig. 4 represents SR as a function of Ton and Toff, whereas the Ip and V remains constant at its middle level. It is observed that the SR values are low when Ton is low with higher Toff or Toff is low with higher Ton. From the analysis it is said that 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.

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.

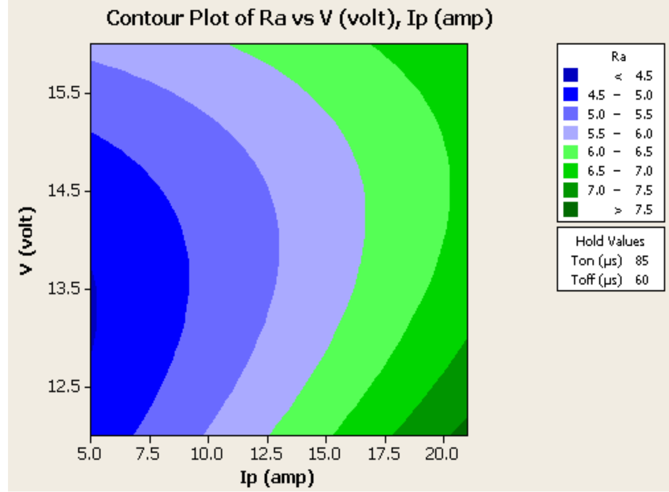

Fig. 5. Effect of Ip & V on SR

4 CONFORMATION TEST

TABLE 6

COMPARISON OF PREDICTED VS. EXPERIMENTAL

Sr. No.	Ip (A)	Ton (μs)	Toff (μs)	Volt (V)	Ra (μm) Predicted	Ra (μm) Experimental
1	17	85	60	14	5.821	5.888
2	13	85	60	12	5.858	5.844

5 CONCLUSION

In the present study, the process parameters with significant influence on Surface roughness were determined by using RSM. This paper highlights 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 of surface roughness. The lower value of surface roughness is achieved with Ip = 6 A, Ton = 75 μs and Toff = 70 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.

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