

Optimization of the EDM Parameters on the Surface Roughness of AISI D3 Tool Steel

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Abstract

The need for machining hard and high strength materials is ever increasing to meet the demands of today requirements. Electrical discharge machining (EDM) is one of these tools used in recent years to cope with these demands. Particular emphasis on the potential of this process was given to surface modification. The influence of EDM parameters on the surface finish of EDMed material was explored. Moreover, this work adopted L9 orthogonal array based on Taguchi method to conduct a series of experiments to optimize the EDM parameters. Experimental data were evaluated statistically by analysis of variance (ANOVA). The EDM parameters are Pulse current (I_p), Pulse –on- time (T_{on}), Pulse –off- time (T_{off}), and the Gap voltage (V_g), while the machining responses in concern are the surface roughness of the machined surface and the over-cut. The experimental results have given optimal combination of input parameters which give the optimum surface finish of the EDMed surface.

Keywords

Surface roughness, pulse current, pulse-on time, pulse-off time, gap voltage

1. Introduction

Technological advances have led to an increasing use of high strength, high hardness and complex shaped materials in manufacturing industries. Traditional machining of these materials is increasingly being replaced by more advanced techniques such as electro-discharge machining (EDM), laser beam machining (LBM), ultrasonic machining (USM), electro-chemical machining (ECM), water jet machining (WJM), etc.

Electrical discharge machining is widely used in mold and die manufacturing. Fallbohmer et al. [1] surveyed applications of the EDM process and pointed out that almost 90% of mold and die makers employed the EDM process to finish the products in USA, Germany, and Japan. Therefore, the EDM technique is an essential approach for mold and die making industries to fabricate their products with superior performance and accuracy. Generally speaking, the application of EDM is not constrained by the hardness, or the material strength of the material to be machined; EDM may be used to machine any conductive material. A further advantage of EDM is that there is no direct contact between the electrode and the component during machining, and therefore no deformation occurs, even for thin components.

Even though EDM technology has proved to be very efficient in machining out complex shapes and also to machine hard materials, there are several problems associated with this machining method. The EDMed components are most likely to contain an uneven fusing structure, globules of debris, shallow craters, micropores, microcracks and pockmarks [2]. The major form of machining damage usually occurs as surface and subsurface damages or cracks. It greatly influences parts during their useful life, especially when such components come in contact with other elements.

Numbers of investigations have been made to characterize the EDM processing of refractory and hard materials [3-7]. Zhang et al. [3] found that longer pulse-on time results in higher surface roughness and generation of a thicker resolidified layer with microcracks on the subsurface. They suggested that the product of thermal conductivity and fusion temperature could be considered as an indicator of EDM machinability. Fu and Li [4] conducted experimental study, in which the pulse current, pulse duration, and electrical polarity were selected as process parameters that affect surface roughness, material removal rate and the variation of fracture strength of Al₂O₃-Cr₃C₂ composites. They observed that the fracture strength and surface roughness of the composites depend strongly on the pulse current and electrical polarity, especially at low energy input. Other researchers [5, 12-15] concluded that surface roughness increases with discharge current and pulse-on time when EDM machining of different engineering materials.

Several techniques have been used to facilitate experimental set-up and design. Taguchi method has been widely used in this concern, and is proven to be a powerful tool to design a high quality system. Moreover, Taguchi method employs a special design of orthogonal array to investigate the effects of the entire machining parameters through small number of experiments. Recently, the Taguchi method was widely employed in several industrial fields and research works. Liao et al. (8) used this method to determine the optimal parameter setting in Wire-EDM. Lin et al. (9) adopted the Taguchi method to obtain the optimal machining parameter of a hybrid process of EDM with ball burnish machining. Yang and Tarn (10) employed this approach to find the optimal cutting parameter for turning operation. Moreover, Bagci and Ozelik (11) used the Taguchi method to explore the effects of drilling parameters on the twist drill bit temperature for a design optimization of cutting parameters. Their works revealed that the Taguchi method was a powerful approach using in design of experiment. The parameter design via Taguchi method can optimize the machining characteristics through the settings of process parameter and reduce the sensitivity of the system performance to sources of variation. The high quality of machining characteristics can be achieved without increasing the operation cost.

Little research has been reported about characterizing of EDMed AISI D3 steel yet for the modeling by surface response methodology. In this work, the effects of machining parameters on EDM machining characteristics were explored. Furthermore, this work adopted an L9 orthogonal array based on Taguchi method to conduct a series of experiments, and statistically evaluate the experimental data by analysis of variance (ANOVA). The main machining parameters such as machining pulse current (I_p), pulse on time (T_{on}), Pulse off time (T_{off}), gap voltage (V) were chosen to determine the surface characteristics of the machined surface embedded in the roughness of the machined surface and the over-cut.

2. Experimental work

Tool steel D3 was used as a test material. This material was selected because of its importance in the industry and tool making. The chemical composition in weight percent is shown in Table 2.1. The material was received in the form of blooms which in turn are sliced into sections of (45mm x 22mm x 15mm) by a sawing machine, then machined by milling machine for the purpose of finishing specimens to the required dimensions. Workpieces are then heat treated in order to increase hardness through hardening at 980C° soaking for 43 minutes and then oil quenching, followed by tempering at 400C° soaking for 60 minutes and then air cooling for the purpose of stress removal. The electrical discharge machining is done by an EDM die sink machine, model ONA CS/HS- 3 axis. Brass electrode (Cu-61.8%, Zn-37.2% and impurities-1.0%) was selected to engrave the workpiece material to produce the shape shown in Fig. 2.1. Commercial grade kerosene was used as the dielectric fluid. Side suction of the dielectric fluid was opted, see Fig. 2.2.

Table (2.1): Chemical composition of tool steel D3 (wt. %)

C	Si	P	Mn	Ni	Cr	Mo	V	Cu	W	Fe
1.07	0.349	0.016	0.422	0.188	12.14	0.084	0.0195	0.057	0.565	Balance

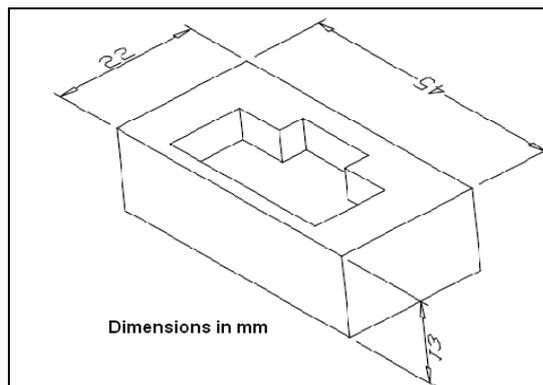


Fig. 2.1: Shape of tool steel die

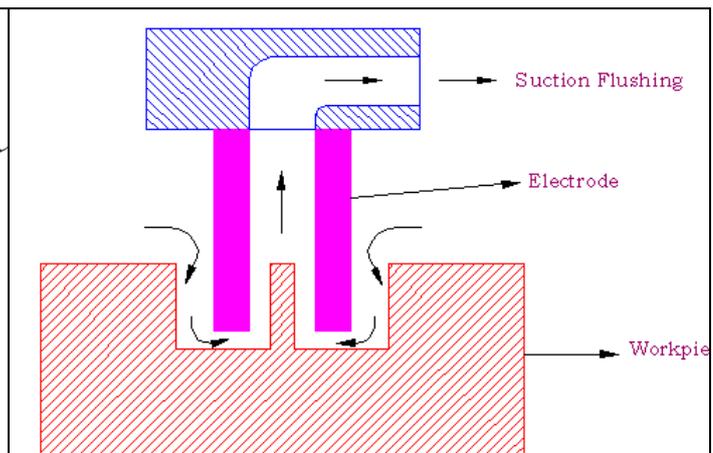


Fig. 2.2 Reverse (suction) flow of dielectric fluid

3. Design Variables

The design variables are divided into two main groups: Input parameters (machining variables) and output measures (response characteristics).

The input parameters are: Pulse current I_p (A), Pulse-on-time T_{on} (μ s), Pulse-off-time T_{off} (μ s), and the Gap voltage V_g (V). The output measures being the roughness of the machined surface of work material (R_a) and the over-cut (OC).

Values of the controllable factors were chosen based on the literature review and capability of the commercial EDM machine used. Different settings of the four controllable factors were used in the experiments and have been divided into three different levels as shown in Table 3.1

Table 3.1. Levels for Controllable Factors.

Symbol	EDM Machining Parameters	Level 1	Level 2	Level 3
I_p	Pulse current (A)	26	36	46
T_{on}	Pulse –on- time (μ s)	50	200	800
T_{off}	Pulse –off- time (μ s)	25	100	200
V_g	Gap voltage (V)	20	45	90

3.1 Analysis of machining variables

The present analysis includes Taguchi's method based on parametric optimization technique to quantitatively determine the effects of various machining parameters on the quality characteristics of EDM process and to find the optimum parametric condition for obtaining optimum machining criteria1 yield. In this analysis, the performed parametric design of experiment is based on the selection of an appropriate standard orthogonal array. The analysis of signal-to-noise (S/N) ratio and ANOVA were carried out to study the relative influence of the machining parameters on the surface roughness of the EDMed material. Based on S/N ratio and ANOVA analysis, the optimal setting of the machining parameters for machined surface roughness and over-cut were obtained and verified.

The main effective plots of the S/N ratios for the output measures are obtained using Minitab 15 software. Plots with the steeper slope along with longer lines shows that the factor has significant impact on the output variable.

3.2 Analysis of Signal-to-Noise Ratio

In Taguchi method, S/N ratio is used to measure the quality characteristics deviating from the desired value. The term signal represents the desirable mean value of the output characteristics and the term noise represents the undesirable value (i.e., standard deviation) for the output characteristics.

To obtain the optimal machining performance the lower the better quality characteristics for surface roughness and over-cut are taken.

The S/N ratio for surface roughness, for j^{th} experiment is defined as:

$$(S/N)_j = -10 \text{Log}_{10} \left(\frac{1}{m} \sum_{i=1}^m y_{ij}^2 \right) \quad (3.1)$$

Where m is the number of replications and y_{ij} is the value of (surface roughness and over cut) of i^{th} replication test for j^{th} experimental condition. Table (3.2) shows the experimental results for surface roughness and the corresponding S/N ratio as per equation (3.1).

Table (3.2). Design of experiments and experimental results for surface roughness and calculated S/N ratio

Exp. N ^o .	I_p (A)	T_{on} (μ s)	T_{off} (μ s)	V_g (V)	Surface Roughness(R_a)			Average R_a, μ m	S/N ratio
J	A	B	C	D	y_{1j}	y_{2j}	y_{3j}	Y_{4j}	
1	26	50	25	20	3.20	2.60	2.34	2.7133	-8.74590
2	26	200	100	45	2.46	2.34	2.20	2.3333	-7.36853
3	26	800	200	90	3.08	2.56	2.42	2.6867	-8.63251
4	36	50	100	90	4.28	4.56	4.76	4.5333	-13.1365
5	36	200	200	20	4.18	5.58	5.96	5.2400	-14.4783
6	36	800	25	45	5.88	6.64	5.86	6.1267	-15.7597
7	46	50	200	45	7.88	7.40	6.08	7.1200	-17.0989
8	46	200	25	90	12.16	9.80	11.96	11.3067	-21.1053
9	46	800	100	20	23.50	19.98	20.46	21.3133	-26.5962

The average S/N ratio for surface roughness for all the factors at different levels is determined, as shown in Table 3.3.

Table 3.3 Average S/N Ratio and Main Effect of surface roughness

Level	I_p	T_{ON}	T_{OFF}	V_g
1	-8.249	-12.994	-15.204	-16.607
2	-14.458	-14.317	-15.700	-13.409
3	-21.600	-16.996	-13.403	-14.291
Delta	13.351	4.002	2.297	3.198
Rank	1	2	4	3

As can be seen from Table (3.3), the surface roughness is most significantly influenced by the pulse current (I_p) followed by the pulse-on-time (T_{on}). The respective values of these parameters are 13.351 and 4.002. The S/N response graph for surface roughness is shown in Fig. (3.1). The greater average S/N ratio corresponds to the minimum surface roughness. From the S/N response graph (Fig. 3.1), it is concluded that the optimum parametric combination is $A_1 B_1 C_3 D_2$ i.e., pulse current of 26 A, pulse-on-time 50 μ s, pulse-off-time 200 μ s and voltage gap 45V. In other words, it is this combination of parameters that gives the better surface finish for the machined material.

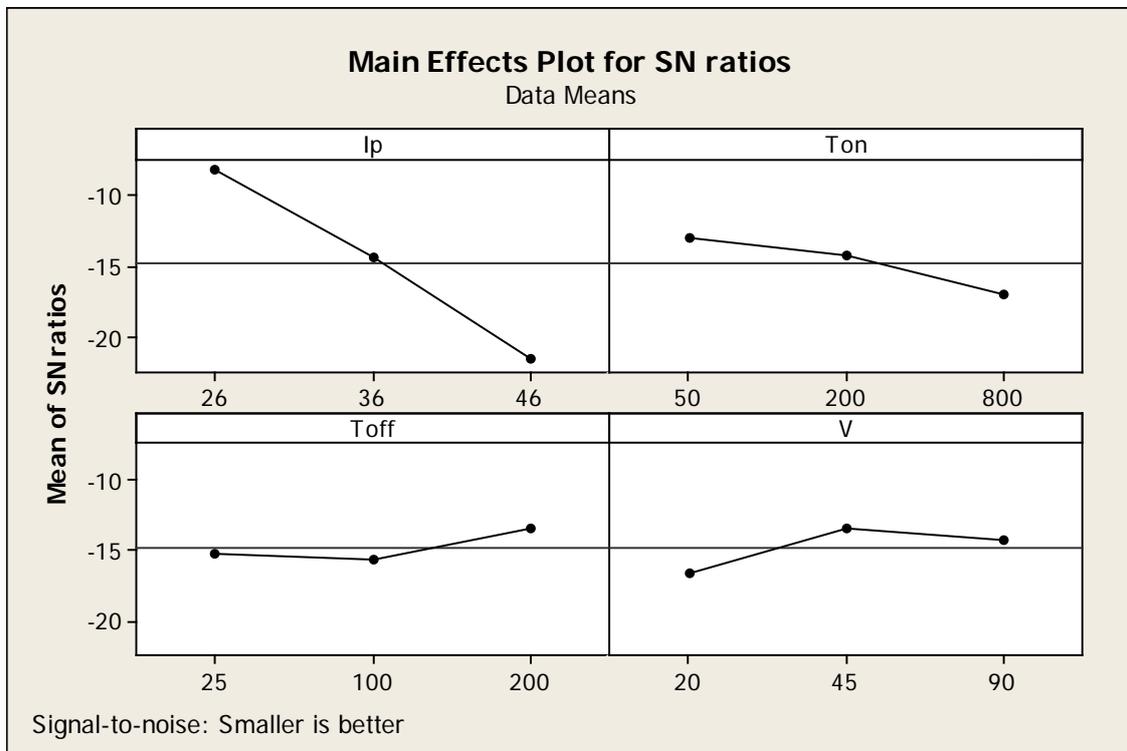


Figure (3.1). Signal-to-noise graph for surface roughens (Ra).

Table (3.4) shows the experimental results for over cut and the corresponding S/N ratio using equation 3.1. The average S/N ratio for over cut for all the factors at different levels is determined as shown in the table 3.5.

Table 3.4 Average for S/N Ratio and Main Effect of over cut

Level	I_p	T_{ON}	T_{OFF}	V_g
1	20.14	20.20	17.06	17.02
2	16.80	18.55	16.94	18.03
3	15.99	14.19	18.39	17.89
Delta	4.14	6.01	1.45	1.01
Rank	2	1	3	4

The pulse-on-time is the most significant factor affecting the over cut value, followed by the pulse current, having delta values of 6.01 and 4.14 respectively.

The S/N response graph for over cut is shown in Fig. (3.2). Greater average values of S/N ratio correspond to the minimum over cut. From the S/N response graph (Fig. 3.2), it is concluded that the optimum parametric

combination is A₁ B₁ C₃ D₂ i.e., pulse current of 26 A, pulse –on –time 50µs, pulse –off –time 200µs and voltage gap 45V.

Table 3.5 Design of experiments and experimental results for over cut and calculated S/N ratio

Exp. N ^o .	I _p (A)	T _{on} (µs)	T _{off} (µs)	V _g (V)	Over cut(OC) mm			Average OC,mm	S/N ratio
j	A	B	C	D	y _{1j}	y _{2j}	y _{3j}	y _{4j}	
1	26	50	25	20	0.095	0.070	0.070	0.078333	22.0239
2	26	200	100	45	0.095	0.080	0.100	0.091667	20.7186
3	26	800	200	90	0.115	0.125	0.150	0.130000	17.6658
4	36	50	100	90	0.105	0.120	0.115	0.113333	18.8997
5	36	200	200	20	0.135	0.125	0.125	0.128333	17.8274
6	36	800	25	45	0.210	0.215	0.195	0.206667	13.6873
7	46	50	200	45	0.110	0.110	0.090	0.103333	19.6792
8	46	200	25	90	0.175	0.130	0.105	0.136667	17.0959
9	46	800	100	20	0.290	0.260	0.275	0.275000	11.2047

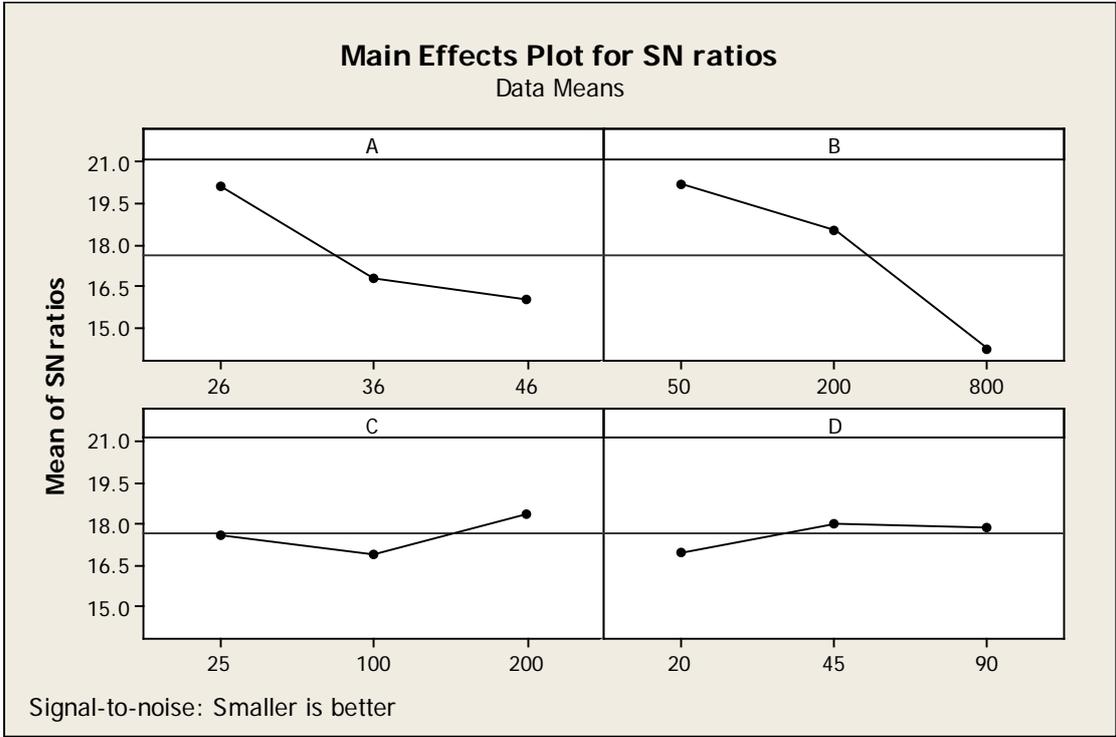


Figure (3.2): Signal-to-noise graph for over cut

4. Analysis of Variance (ANOVA)

In this investigation, the analysis of variance (ANOVA) is performed to determine which machining parameter significantly affects the quality characteristics of EDM process and also to find the relative contribution of machining parameters in controlling the responses of the EDM process. To accomplish ANOVA, the total sum of squared deviation (SS_T) from the total mean S/N ratio can be determined as:

$$SS_T = \sum_{j=1}^N ((S/N)_j - (S/N)_m)^2 \dots\dots\dots (4.1)$$

Where N is the total number of experiments and (S/N)_m is the grand mean of S/N ratio. The total sum of SST is decomposed into two sources: (i) the sum of squared deviations due to each machining parameters (SS_A, SS_B, SS_C and SS_D) and (ii) the sum of squared error (SS_E). To perform F (variance ratio) test,

the mean squared deviation due to each design parameter is calculated. The mean of squared deviation is equal to SS_T divided by the number of Degrees of freedom (DOFs) associated with the design parameters. The F-value for each design parameter is the ratio of the mean of the squared deviation to the mean of squared error. The percentage contribution by each of the design parameters is a ratio of the value of sum of squared of each design parameters to the total sum of squared for all the design parameters.

Table 4.1 shows the results of ANOVA for surface roughness.

Table 4.1 Results of ANOVA for Surface Roughness.

Symbol	Machining parameter	Degrees of freedom	Sum of squares	Mean squares	F	Contribution %
A	Pulse current	2	267.815	133.908	--	84.25
B	Pulse-on-time	2	24.946	12.473	--	7.85
C	Pulse-off-time	2	8.765	4.383	--	2.75
D	Gap voltage	2	16.365	8.183	--	5.15
Error		0	---	---	--	
Total		8	317.892			100.00

It is found that the pulse current has the most significant effect on surface roughness of EDM process. The pulse-on-time, pulse-off-time and voltage gap has very little effect on R_a compared to the pulse current parameter of EDM process. it is necessary to pool the factor having less influence for correct interpretation of results, see Table 4.2. From the calculated values of F, it is concluded that at 99 per cent confidence level, the machining parameter (A) have significant effect on R_a as the calculated value of F is greater than the value of $F_{0.01}(2,6) = 10.925$.

Table 4.2 Pooled ANOVA for Surface Roughness.

Symbol	Machining parameter	Degrees of freedom	Sum of squares	Mean squares	F	Contribution %
A	Pulse current	2	267.815	133.908	16	79
B	Pulse-on-time	(2)	Pooled	Pooled	---	---
C	Pulse-off-time	(2)	Pooled	Pooled	---	---
D	Voltage gap	(2)	Pooled	Pooled	---	---
(Error)		(6)	(50.077)	(8.346)	---	21
Total		8	317.892	---	---	100

Table 4.3 shows the results of ANOVA for over cut. It is found that the pulse-on-time has the most significant effect (63.1%) on over cut of EDM process. The pulse current has moderate effect (31.5%), while the pulse-off-time and voltage gap respectively have very little effect on the over cut.

Table 4.3 Results of ANOVA for over cut.

Symbol	Machining parameter	DF	SS	MS	F	Contribution
A	Pulse current	2	28.9190	14.4595	---	31.5
B	Pulse-on-time	2	57.9361	28.9680	---	63.1
C	Pulse-off-time	2	3.1608	1.5804	---	3.45
D	Voltage gap	2	1.7937	0.8969	---	1.95
Error		0	---	---	---	
Total		8	91.8096			100

Though, for correct interpretation of results; it is necessary to pool the factors having less influence, see Table 4.4. From the calculated value of F, it is concluded that the machining parameters A and B have significant effect on over cut as the calculated value of F is greater than the value of $F_{0.05}(2,4) = 6.94$.

Table 4.4 Pooled ANOVA for over cut.

Symbol	Machining parameter	DF	SS	MS	F	Contribution %
A	Pulse current	2	23.9645	11.9822	9.67	26.1
B	Pulse-on-time	2	52.9816	26.2908	21.2	57.7
C	Pulse-off-time	(2)	Pooled	--	--	--
D	Voltage gap	(2)	Pooled	--	--	--
Error		4	4.9545	1.2386	--	16.2
Total		8	91.8096			100

5. Confirmation Tests

By selecting the optimal level of design parameters, the final step is to verify and confirm the obtained (predicted) parameters to those found through experimental work to assess the quality characteristics of the EDM process. The predicted optimum value of S/N ratio $(\bar{S/N})_p$ can be determined as

$$(\bar{S/N})_p = (S/N)_m + \sum_{j=1}^p ((S/N)_j - (S/N)_m) \dots\dots\dots (5.1)$$

Where $(S/N)_m$ is the grand mean of S/N ratio, $(S/N)_j$ is the mean S/N ratio at the optimum level, and p is the number of main design parameters that affects the quality characteristics.

Table 5.1 shows a comparison of the predicted surface roughness (Ra) with the actual (Ra) using the optimal machining parameter. Good agreement between the predicted and the actual Ra is observed.

Table 5.1 Results of confirmation experiments for surface roughness (Ra)

Level	Optimal machining parameters	
	Predicted	Experimental
Surface roughness (Ra)	A ₁ B ₁ C ₃ D ₂ 1.539	A ₁ B ₁ C ₂ D ₂ 2.333
S/N ratio	-3.747	-7.368

Table 5.2 shows a comparison of the predicted over cut with the actual over cut using the optimal machining parameter. Good agreement between the predicted and the actual OC can also be observed.

Table 5.2: Results of confirmation experiments for over cut (OC)

Level	Optimal machining parameters	
	Predicted	Experimental
Over cut (OC)	A ₁ B ₁ C ₃ D ₂ 0.064	A ₁ B ₁ C ₁ D ₁ 0.078
S/N ratio	23.822	22.121

6. Conclusions:

From the experimental results, S/N ratio and ANOVA analysis and predicted optimum machining parameters, the following conclusions are drawn:

- 1) Pulse current is the one influential parameter (in rank order based on percentage contribution) which significantly affect the surface roughness. The pulse-on-time, pulse-off-time and gap voltage are less influential parameters (in rank order based on percentage contribution) which insignificantly affect the surface roughness.
- 2) The surface roughness on the machined surface varies through all the experiments from 2.3 to 21.3 μm. From the outlined results and analysis it is clear that a higher pulse current and longer pulse-on- time cause a poorer surface finish. This can be attributed to the fact that a higher pulse current and a longer pulse-on -time may cause more frequent cracking of the surface. More frequent melt expulsion also occurs, this leads to the formation of deeper and larger craters on the surface of the workpiece. Results shown in Fig. 3.1 indicate that the best surface finish can be obtained by setting

the EDM machine parameters at low pulse current and small pulse-on-time. This trend agrees with the results reported by previous investigators [12,15].

- 3) (3) According to the proposed levels of control factors used in this work, minimum surface roughness (Ra) can be achieved by selected combination of parameters, $A_1 B_1 C_3 D_2$ i.e., pulse current of 26 A, pulse-on-time 50 μ s, pulse-off-time 200 μ s and voltage gap 45V.
- 4) Pulse-on-time and Pulse current are the two influential parameter, in rank order, which significantly affect the over cut. The pulse-off-time and gap voltage are less influential.
- 5) For achieving minimum over cut (OC), the optimum level of parametric conditions are $A_1 B_1 C_3 D_2$ i.e., pulse current of 26 A, pulse-on-time 50 μ s, pulse-off-time 200 μ s and voltage gap 45V.

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