Process Parameters Optimization for Material Removal Rate & Surface Roughness in EDM of En31 Tool Steel

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***Abstract*—To machine materials for dies, complex cavities & intricate jobs, a non-conventional machining process called electrical discharge machining is used. Areas like aeronautics, die & mold manufacturing, Injection molding etc. find a wide range of applications in this process. Improving the MRR, reducing the tool wear rate & surface roughness is the main challenge for an EDM researcher.**

The present study aims at presenting the optimization of die sinking EDM. For obtaining the overall utility value which depicts the overall performance of EDM, Multi-response, optimization techniques is being taken into considerations. The present study reveals the investigation of process parameters on Current, Pulse on time, duty cycle, voltage, spark gap and flushing pressure for Metal removal rate (MRR) and Surface Roughness (SR). The maximum effect on Utility is shown by the pulse on time then flushing pressure, current, spark gap and voltage have their effect but duty cycle proved to be an insignificant factor as shown by the experimental results. The optimum values of MRR & SR are 0.252 g/min & 5.02 µm respectively. The results are further verified by the confirmation experiments.

***Index Terms*—EDM, MRR, SR, Taguchi method, Utility concept, Optimization**

I. Introduction

Machining process that is best suited for making the dies in extrusion or forging industry is an unconventional machining process called Electrical discharge machining [1]. There are many hard materials like composites, High strength temperature resistant (HSTR) Super alloys which can be machined by this process [2]. In spite of improved process capabilities slow material removal rate is the main drawback with this process. The influence of factors like the pulse on time, current, duty cycle, voltage, spark gap & flushing pressure on response characteristics like

MRR, TWR, & SR to achieve the optimum MRR, and accuracy[3]. Some settings can lead to the different results for other quality characteristics but an individual setting of input parameters for specified multi-response parameters is desirable. The study has developed a simple method which is based on Taguchi methodology & utility concept. [4-6].

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II. Literature Survey

In the recent times, to improve the desired quality characteristics the researchers have actually tried to quantify the process parameters. The machined component's quality in die sinking EDM is affected by a large number of machining parameters revealed by literature review and the characteristics affecting the material removal rate, tool wear and surface roughness are identified by the researchers [7-11]. In order to obtain the highest MRR with the minimum erosion of tool is the rapid demand of the industry. The material of the electrode highly influences the sparking mechanism in EDM and also the workpiece with the removed debris in dielectric [12].An Introduction to uniform tool wears machining method compensating the wear in the longitudinal direction by the application of to and fro machining motion has been observed[13]. The development of the part geometry and tool wear through the simulations of geometry is given by Bleys et al [14-15]. Cancogun et al investigated the variation of electrode edge wear and machining performance outputs, with the variation of machining parameters in die sinking EDM. The profiles obtained were modeled & the variations of radii of the circular arcs with machining parameters were given. The edge wear profiles of electrodes were observed accurately in the exponential function models [16]. The multi-criterion optimization in the same machine that improved the electrode wear, surface finish and metal removal rate was presented by Osyezka et al [16]. The major optimum factor was presented by Lin et al using Taguchi technique along with fuzzy algorithm, for enhancing the quality characteristics of electrode wear and MRR [16-19]. Navdeep Malhotra et al optimized the machining parameters with an objective to achieve high MRR in EDM. Experimentation was done on EN 31 with copper tools by varying several parameters. The study revealed that the MRR increases with the increase in current, voltage and spark gap & it decreases with increase in pulse on Time. [20]

III. Principle of Die Sink EDM

The application of Die sinking EDM is in machining thin & deep cavities in hard to machine materials [21].

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Removing the material by spark erosion between the electrode and the workpiece is the main principle of EDM [22]. A series of discrete electrical discharges, that occurs between the tool & the job by which electrical energy is used in metal erosion mechanism [23]. With a temperature range of 8000^{o}C to 20,000^{o}C, plasma is generated between the anode & the cathode [24]. The process helps in giving the accurate shape by using the electrode which is the replica of the cavity in the job governing the zone in which the spark erosion is occurring. [25], [26]

IV. SELECTION OF PROCESS PARAMETERS

Electrical parameters, Nonelectrical parameters & Electrode-based parameters are the three process parameters that affect the performance of Electric Discharge Machining [27]. The selected parameters for the study are Pulse on time, Current, Voltage, Spark gap, Flushing pressure & duty cycle [28].

By conducting the pilot experiment using a single variable at one time, levels of all these parameters are decided.

A. Response Characteristics

Material Removal Rate (MRR) & Surface Roughness (SR) are the response characteristics selected for the study. For optimizing the performance of EDM, the multi-characteristic optimization with the utility technique has been used [29].

TABLE I. INPUT PARAMETERS FOR MATERAIOL REMOVAL RATE

Input Parameters	**Range**
Spark Gap	0.3--0.7
Pulse On Time	100—200
Discharge Current	6—12
Voltage	35—55
Flushing Pressure	0.4--0.8
Duty cycle	56—88

TABLE II. INPUT PARAMETERS HAVING CONSTANT VALUES

Electrode	The tool is made of Copper, cylindrical shape with a central circular cavity having diameter 20 mm & length 30 mm.
Job	An EN31 material having hardness value 58 HRC, Cylindrical in shape with a central groove of 3mm diameter.
Polarity	The tool is having Negative Polarity & the workpiece have positive polarity.
Dielectric	Kerosene is used as the dielectric with center flushing.

V. UTILITY CONCEPT

On various quality characteristics, the performance of the product can be evaluated. In this case, a composite index is given to quality characteristics which are combined. The utility of is demonstrated by such an index and it is the sum of each quality characteristics. The expression for a joint function is given by equation 1

$$U= \sum_{i=1}^{n} W_i U(x_i) \quad (1)$$

TABLE III. OPTIMUM VALUES OF RESPONSE PARAMETERS

Response characteristics	S.I. Units	Setting of machine	Optimum value
MRR	g/min	A_3,B_1,C_3,D_1,F_1	0.228
TWR	g/min	A_1,B_3,C_3,D_3,F_1	0.0071
R_a	µm	A_1,B_1,C_1,D_1,E_2,F_3	4.989

Where, W_i the summation of all the weights for all attributes should be equal to 1.

By maximizing the overall utility, the response characteristic considered for evaluation of utility will be optimized automatically.

A Calculation of Utility Value

There is a need for constructing the preference scale for every characteristic for determining the utility value for specified response parameters. To obtain a composite number, these scales are weighted. To satisfy the point of differences on different quality characteristics this weight is done. [30].If a logarithmic preference scale is used, the least acceptable quality is 0 and the best quality level is 9. For a chosen logarithmic scale, the preference scale is given as [31-35]

$$P_i = A \log \frac{x_i}{x_i'} \quad (2)$$

End use of the product or customer's requirements affects this thing. Considering the following condition in equation 3, the weights should be assigned

$$\sum_{i=1}^{n} W_i = 1 \quad (3)$$

The value of utility can be calculated as under:

$$U_j = \sum_{i=1}^{n} W_i P_i \quad (4)$$

VI. MULTI-RESPONSE OPTIMIZATION

Table III shows the optimum settings of the input characteristics and the optimum values of the tool wear, surface roughness and metal removal rate which are optimized using one variable at a time approach.

VII. UTILITY CONCEPT OF MRR & SR

A. Predicted Construction of Scale

1) Metal removal rate (MRR)

The equation 5 represents the preference scale for MRR. For convenience the equation 5 is reproduced here:

$$P_{MRR} = 28.26 \log \frac{x}{0.111} \qquad (5)$$

2) Surface roughness (SR)

X^* = optimal value of SR (using single response optimization technique)
= 4.989μm

X' = maximum value of MRR
= 8.890μm (assumed)

By the use of above values, the preference scale for SR being constructed is given as under:

$$P_{SR} = -35.87 \log \frac{x}{8.890} \qquad (6)$$

B. *Quality Characteristics Weightage Value*

Equal weighting is being assigned assuming equal importance to both the quality characteristics.

W_{SR} = Weightage for surface roughness
= 0.5

W_{MRR} = Weight value of MRR
= 0.5

C. *Utility Value Calculation*

This can be calculated by the following equation:

$U(n, R) = P_{SR}(n, R) * W_{SR} + P_{MRR}(n, R)*W_{MRR}$

Where, n = 1 to 27

R = repetition, R = 1 to 3

Table 5 shows calculated values of utility.

D. *Calculation of Optimum Settings of Input Parameters*

Analysis has been done on the utility values for mean responses to noise ratios. To find the type of S/N ratio, the utility needs to be checked. The mean value of the signal to noise ratios and its main effects are given in Table 7(a). The data from Tables 6(a) and 7(a) are plotted in Figure 1.

From the Figure 1, the third level of current (A3), first level of pulse on time (B1), second level of spark gap (C2), first level of voltage (D1), second level of duty cycle (E2) and third level of flushing pressure (F2) will give the good performance with respect to utility value and S/N ratio in the required limits of input parameters. The pooled Analysis of Variance is given in Table 6(b). As seen from the Tables 6(b) and 7(b), current, pulse on time, voltage and duty cycle has the significant role in affecting the utility values.

The percentage contribution calculated reveals that the current (A: 9.662%), pulse on time (B: 19.942%), and voltage (D:10.814%) have significantly larger influence than duty cycle (D: 2.046%) in affecting the mean value of the utility. The current and spark gap (A*C), interactions between current and pulse on time (A*B), pulse on time and spark gap (B*C) are also quite significant in contributing the mean response. Table 8.7(b) indicates that the pulse on time has maximum influence in controlling the variation around mean value of utility (B: 18.29%), followed by current (A: 16.82%), voltage (D: 14.83%). It is also revealed from ANOVAs that the interactions between current and pulse on time, pulse on time and spark gap are significant in both the ANOVAs, and thus affects the mean and variation around the mean of utility. The optimal setting of input parameters is as follows:

TABLE IV. SPECIFICATION OF CURRENT

Parameters		Level	
Current	(A)	3	12A
Pulse on Time (T_{on})	(B)	1	100μSec
Voltage	(D)	1	35mm
Duty cycle	(E)	2	9

TABLE V. UTILITY VALUE ON RESPONSE CHARACTERISTICS
（a）Material Removal Rate (b) Surface Roughness (c) TWR

RAW DATA (UTILITY VALUES) MRR, TWR and SR)			MSD (HB)	S/N RATIOS
R1	R2	R3		
7.011	6.836	6.756	0.021	16.733
4.550	4.637	3.354	0.061	12.130
3.871	3.335	3.168	0.085	10.684
2.554	2.145	2.419	0.181	7.434
3.433	3.318	3.078	0.094	10.281
4.910	4.483	4.381	0.048	13.207
6.490	5.338	4.646	0.035	14.552
6.674	5.509	6.222	0.027	15.674
4.764	4.461	4.841	0.046	13.404
7.592	7.230	7.306	0.018	17.351
6.566	5.981	6.326	0.025	15.955
6.487	6.388	5.780	0.026	15.839
1.002	0.175	0.026	488.594	-26.889
4.230	3.866	4.122	0.061	12.179
3.141	2.497	2.820	0.129	8.888
4.734	3.785	4.083	0.058	12.355
2.464	2.573	1.538	0.246	6.088
0.886	0.758	0.996	1.340	-1.272
7.240	5.135	6.096	0.028	15.533
5.771	5.332	5.227	0.034	14.694
4.091	4.507	4.229	0.055	12.600
3.234	4.800	5.012	0.060	12.246
3.477	4.803	4.422	0.059	12.287
6.340	7.490	5.932	0.024	16.251
3.882	4.737	3.749	0.061	12.169
5.338	5.743	4.678	0.037	14.314
6.498	6.180	6.610	0.024	16.153

TABLE VI. a) MEAN VALUES AND MAIN EFFECTS

Input parameter	Mean Utility Values			Main Effects	
	L_1	L_2	L_3	L_2-L_1	L_3-L_2
A	4.5623	3.8278	5.2057	-0.7345	1.3779
B	5.5852	3.6336	4.3770	-1.9516	0.7433
C	4.5630	4.5642	4.4386	-0.0289	-0.1255
D	5.3674	4.0289	4.1995	-1.3384	0.1706
E	4.1998	4.8589	4.5371	0.6591	-0.3218
F	4.4219	4.4965	4.6774	0.0746	0.1809
A*B	4.1418	4.4066	5.0474	0.2648	0.6408
A*C	4.6755	4.5000	4.4204	-0.1755	-0.0796
B*C	5.1089	4.3756	4.1113	-0.7333	-0.2643

TABLE VI (b) POOLED ANOVA

Source	Sum of squares	Degree of freedom	V	F-Ratio	SS'	Percentage contribution
A	25.6673	2	12.83365	46.3*	25.1198	9.662
B	52.3918	2	26.19592	94.5*	51.8443	19.942
C	0.36388	2	Pooled	-	-	-
D	28.6599	2	14.32993	51.7*	28.1124	10.814
E	5.8653	2	2.93265	10.6*	5.31779	2.046
F	0.932	2	Pooled	-	-	-
A*B	73.2434	4	18.31085	66.1*	72.1484	27.752
A*C	9.73905	4	2.434763	8.8*	8.64403	3.325
B*C	47.7792	4	11.9448	43.1*	46.6842	17.957
T	259.972	80				100.000
e_p	16.6261	60	0.27710		22.1012	8.502

TABLE VII. (a) MEAN SIGNAL TO NOISE RATIOS AND ITS MAIN EFFECTS

Input Parameter	**Means of Surface Roughness (Ra)**			**Main Effects**	
	L1	**L2**	**L3**	**L2-L1**	**L3-L2**
A	**12.68**	**10.03**	**14.03**	**-2.65**	**4.00**
B	**14.61**	**10.48**	**11.63**	**-4.13**	**1.15**
C	**12.22**	**12.62**	**11.89**	**0.40**	**-0.73**
D	**14.34**	**11.37**	**11.02**	**-2.97**	**-0.35**
E	**11.14**	**13.27**	**12.33**	**2.14**	**-0.94**
F	**11.89**	**12.06**	**12.77**	**0.17**	**0.71**
A*B	**11.31**	**11.94**	**13.48**	**0.63**	**1.54**
A*C	**12.37**	**12.06**	**12.30**	**-0.31**	**0.23**
B*C	**13.22**	**11.88**	**11.63**	**-1.34**	**-0.24**

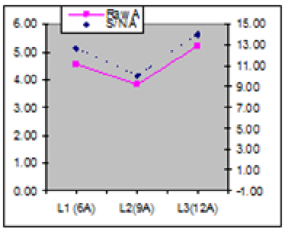
TABLE VII (b) POOLED ANOVA

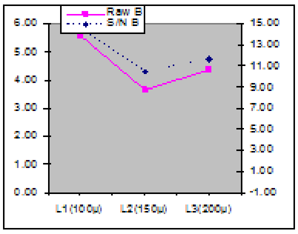
Source	Sum of squares	Degree of freedom	V	F-Ratio	SS'	Percentage contribution
A	74.54	2.00	37.27	4.53*	67.28	16.82
B	81.72	2.00	40.86	4.78*	74.46	18.29
C	2.41	2.00	Pooled	-	-	-
D	59.99	2.00	30.00	4.04*	52.73	14.83
E	20.62	2.00	-	-	-	-
F	3.92	2.00	-	-	-	-
A*B	131.82	4.00	32.96	4.24*	117.30	26.09
A*C	18.24	4.00	-	-	-	-
B*C	86.33	4.00	21.58	3.47*	71.80	18.75
T	486.86	26.00				100.00
e_p	176.62	12.00	14.72		227.46	5.22

Quality Characteristics (Type) : HB Type

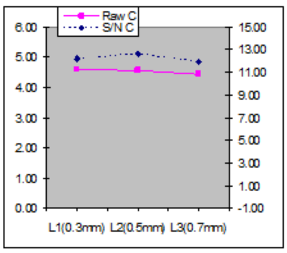
Raw Data Utility :———————

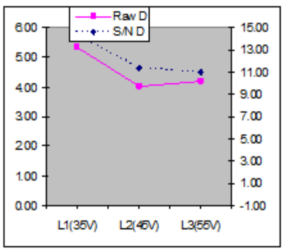
S/N Ratio Utility : -------------------



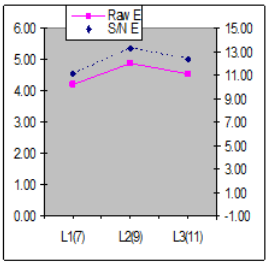


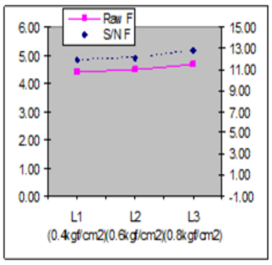
(a) Pulse on Time (µsec) (b)Current (A)





(c) Spark Gap (mm) (d) Voltage (V)





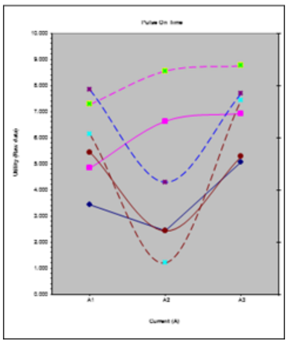
(e) Duty cycle (f) Flushing Pressure

Figure 1. Effects of Input characteristics Interactions on MRR & S/N ratios.

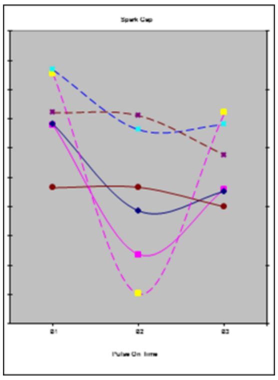
Raw Data (N) : ______________

S/N Ratio (dB) : - - - - - - - - - - - - -

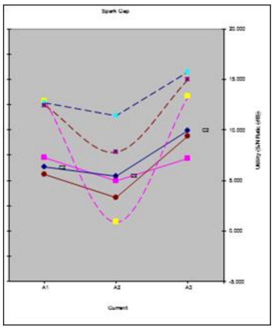
Characteristic : Higher the Better



(a)



(b)



(c)

Figure 2. Effects of Input characteristics Interactions on MRR & S/N ratios.

(V) Calculations of predicted optimum Utility

The average utility values as obtained from table 5 and 6(a)

$\overline{A_3}$ = 5.2057

$\overline{B_1}$ = 5.58

$\overline{C_2}$ = 4.56

$\overline{D_1}$ = 5.367

$\overline{E_2}$ = 4.859

Average of material removal rate ($\overline{T}$ $_{U\ (MRR,\ SR)}$) = 4.456

The percentage contribution of each of the input parameter is shown in last column of Table 6 (b). It is clear that the relative strength of interaction between current and spark gap (A*C: 3.325%), an interaction between pulse on time and spark gap (B*C: 17.957%) and the interaction between current and pulse on time (A*B: 27.75%) are significant. Thus it is pertinent to include interactions (A*B, B*C and A*C) in the calculation of mean and confidence interval. To obtain the best estimate of mean value when an interaction is present, the trials that include that specific treatment conditions [(A_3B_1), (B_1C_2) and (A_3C_2)] would be taken as average (Ross 1996).

As obtained from the 2(b),

$\overline{A_3B_1}$ = 6.923

$\overline{B_1C_2}$ = 6.830

$\overline{A_3C_2}$ = 5.977

The predicted optimal Utility ($\mu_{U_{(MRR,SR)}}$) can be calculated as (Ross 1996 p 185):

$$\mu_{U_{(MRR,SR)}} = \overline{A_3B_1} + \overline{B_1C_2} + \overline{A_3C_2} + \overline{D}_1 + \overline{E}_2 - \overline{B}_1 - \overline{A}_3 - 2\overline{C}_2 \tag{7}$$

$\mu_{U_{(MRR,SR)}}$ = 6.923+6.830+5.977+5.367+4.859-5.58-5.2057-2*4.56

= 10.050

For the confidence intervals of 95%, Cl_{POP} and CI_{CE} have been calculated using Eqs.8 and 9. The equations are given below for ready reference:

$$CI_{POP} = \sqrt{\frac{F_\alpha(1, f_e)V_e}{n_{eff}}} \tag{8}$$

$$CI_{CE} = \sqrt{F_\alpha(1, f_e)\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]V_e} \tag{9}$$

The specific values as required in Eqs.8 and 8 are

$f_e = error \quad DOF = 60$ (Table 6b)

V_e = error variance =0.27710 (Table 6b)

N = 81: n_{eff} = 81/21 (calculated); R=3

So CI_{POP} = ±0.536

CI_{CE} = ±0.81084

The 95% confidence intervals are

$$\text{CI} : (\hat{\mu}_{U_{(MRR,SR)}} - CI) < \mu_{U_{(MRR,SR)}} < (\hat{\mu}_{U_{(MRR,SR)}} + CI) \tag{10}$$

Hence,

CI_{POP} = 9.514 < $\mu_{U_{(MRR,SR)}}$ < 10.586

CI_{CE} = 9.239< $\mu_{U_{(MRR,SR)}}$ < 10.861To

E Confirmation Experiments

At the optimum setting (A_3, B_1, C_2, D_1, E_2) of the process parameters, three confirmation experiments have been conducted. The following values are determined as follows:

(a) Mean metal removal rate = 0.252g/min

(b) Average surface roughness = 5.02µm

The utility can be calculated by using following equation:

$$U = P_{SR} * W_{SR} + P_{MRR} * W_{MRR}$$

$$\mu_{U_{(MRR,SR)}} = 9.725$$

VIII. Conclusion

(a) The contribution (in percentage) of the significant input parameters to optimize utility index for the required response characteristic is shown as under:

Voltage : 10.814%

Current : 9.662%

Pulse on time : 19.942%

Duty cycle : 2.046%

Interaction between current and spark gap : 3.325%

Interaction between current and pulse on time : 27.752%

Interaction between pulse on time and spark gap : 17.957%

(b) The best levels of various input parameters for optimization of Utility ($\mu_{U_{(MRR,SR)}}$ = 10.050) are Current-12 A, Duty Cycle=9, Pulse On time-100µs, Voltage=35V.

(c) The calculated range of utility based on MRR & SR ($\mu_{U_{(MRR,SR)}}$) at 95% confidence level are :

$CI_{POP} = 9.514 < \mu_{U_{(MRR,SR)}} < 10.586$

$CI_{CE} = 9.239 < \mu_{U_{(MRR,SR)}} < 10.861$

(d) The optimum values determined by the use of multi-response optimization technique is being confirmed by using confirmation experiments.

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