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Multi Response Optimization of material removal rate and Overcut in EDM using RSM

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Abstract: *In this experimental study, attempts have been made to model and optimize EDM process parameters of die steel using different electrode shape namely, cylindrical, rectangular, and hexagonal shape based on Response Surface Methodology (RSM) by using statistical software, Design Expert (DX-6). Four independent input parameters, viz., pulse on time, pulse off time, peak current and tool shape were performed to explore the influence on material removal rate and overcut. The regression equation, and ANOVA was developed using the experimental data and graphs were plotted to investigate the effect of process variables on response characteristics. Multi response optimization was carried out using desirability function in conjunction with RSM to overcome the problem of contradictory responses of single response optimization. From the experimental data of RSM, empirical model were developed and the confirmation experiments were performed, which were found within 95% confidence interval. Optimal setting for multi response characteristics means for both MRR and Overcut are 33.84Amp IP, 10µs Ton, 5.10µs Toff, for the hexagonal shape of electrode.*
Keywords: *Die steel, EDM, MRR, Overcut, RSM, Multi Response Optimization*

I. Introduction

Die steel is a cold work steel. It is an ideal and widely used type of hardened steel which is very economical and dependable for gauging, cutting and blanking tools as well as can be relied for hardness and good cutting performance. It is well known that conventional machining methods are inadequate to produce complex geometrical shapes in the hard and temperature-resistant alloys like die steels as discussed by **Shankar Singh et al. (2004)**. EDM has been widely used to produce dies and moulds to produce complex geometrical shapes. In EDM, the removal of material is based upon the electro-discharge erosion (EDE) effect of electric sparks occurring between two electrodes (cathode and anode) that are separated by a dielectric liquid. Metal removal takes place as a result of the generation of extremely high temperatures generated by the high-intensity discharges that melt or evaporate workpiece.

Hao Tong et al. (2008) was introduced the method of assisting workpiece vibration to improve the machining efficiency and accuracy, into such micro-EDM process using the tool electrodes with non-circular cross-section structures. **G. Skrabalak et al. (2013)** presented performance characteristics of the process, using various gases and their mixtures as dielectric medium. **Sengottuvel. P et al. (2013)** investigated the effects of various EDM input parameters as well as the influence of different tool geometry on Material Removal Rate(MRR), Tool Wear Rate(TWR) and Surface Roughness(SR) on machining of Inconel 718 material by using copper electrode. **I.J. Mikesic et al. (2009)** presented a novel tooling concept that relates to a set of standard prismatic tools of an oblong section, which incorporate the favorable functional characteristics of both ED-milling and die-sinking technologies. **M. K. Das et al. (2013)** optimized the multi response problems using weighted principal components analysis (WPCA) method. The optimum combination of process parameters has been found out and verified through the confirmation test. **S. Assarzadeh, and M. Ghoreishi (2013)** optimized process parameters in Electro-Discharge Machining (EDM) of tungsten carbide-cobalt composite (ISO grade: K10) using cylindrical copper tool electrodes by employing Response surface methodology (RSM). The obtained predicted optimal results were also verified experimentally and the values of confirmation errors were computed, all found to be satisfactory, being less than 10%.

II. Experimentations

Various input process parameters varied during the experimentation are pulse on time, pulse off time, peak current and tool shape. Apart from the parameters mentioned above following parameters were kept constant at a fixed value during the experimentation

1. Work piece : Die Steel
2. Electrode(tool) : copper
3. Work piece height : 10mm
4. Dielectric Conductivity : 20mho

5. Dielectric temperature : 20-24^{0}C

In the present work two important response variables viz. material removal rate (MRR) and taper cut were being measured and studied. Every time the material is removed from the work piece due to the heat generated by the spark, at the same time generation of small micro holes due to thermal damage some taper effect generation on micro holes.

III. Results and Discussions

The influences of different input parameters i.e. spark current, pulse off time, pulse on time, and electrode shape on response factors i.e. MRR and Overcut in the experiments performed with the help of Response surface methodology method are being discussed. A scientific approach to planning and conducting of experiments on EDM was incorporated in order to perform the experiments most effectively. RSM approach was taken as the basis for planning and conducting the experiments so that the appropriate data is collected which may be analyzed to obtain valid and objective conclusions. Table 1 shows the ranges of the selected control factors for experimentations.

Table 1: Control factors and their Ranges

Real Factor	Coded Factor	Parameter Name	Unit	Lower Limit	Upper Limit
Ip	A	Peak Current	(Amp)	5	35
Ton	B	Pulse On Time	(μs)	2	10
Toff	C	Pulse Off Time	(μs)	2	10
TS	D	Tool shape		Circular, Rectangular, & Hexagonal	

A well designed experimental plan can substantially reduce the total number of experiments. Box Behnkan designs are one of those means. Preceding a step ahead, Box Behnkan designs of second order have been found to be the most efficient tool in RSM to establish the mathematical relation of the response surface using the smallest possible number of experiments without losing its accuracy.

Table 2: Design of Experiments and Response Data

Run	A: IP	B: Ton	C: Toff	D: TS	MRR	Overcut
1.	20.00	10.00	2.00	2.00	9.1	4.08
2.	20.00	2.00	6.00	1.00	3.18	1.15
3.	20.00	2.00	2.00	2.00	5.64	2.62
4.	20.00	6.00	10.00	1.00	10.61	5.45
5.	20.00	2.00	6.00	3.00	4.59	2.29
6.	20.00	6.00	6.00	2.00	8.54	4.19
7.	5.00	6.00	6.00	3.00	6.76	3.63
8.	20.00	10.00	10.00	2.00	5.41	2.49
9.	20.00	6.00	6.00	2.00	13.73	6.49
10.	35.00	6.00	2.00	2.00	16.65	8.49
11.	5.00	6.00	10.00	2.00	2.95	1.22
12.	20.00	6.00	10.00	3.00	10.08	5.95
13.	5.00	6.00	6.00	1.00	5.77	2.49
14.	20.00	6.00	6.00	2.00	9.79	4.82
15.	20.00	6.00	2.00	1.00	16.28	8.09
16.	35.00	6.00	6.00	3.00	19.38	8.52
17.	35.00	10.00	6.00	2.00	14.21	7.82
18.	5.00	10.00	6.00	2.00	2.47	1.82
19.	20.00	6.00	2.00	3.00	14.07	7.28
20.	35.00	6.00	6.00	1.00	21.7	10.05
21.	20.00	6.00	6.00	2.00	9.1	5.49
22.	20.00	10.00	6.00	1.00	12.71	6.85
23.	20.00	6.00	6.00	2.00	10.93	5.82
24.	5.00	6.00	2.00	2.00	9.23	4.12
25.	20.00	2.00	10.00	2.00	4.48	2.82
26.	20.00	10.00	6.00	3.00	5.62	2.28
27.	35.00	6.00	10.00	2.00	13.7	6.35
28.	5.00	2.00	6.00	2.00	1.14	1.04
29.	35.00	2.00	6.00	2.00	9.67	4.82

ANOVA For MRR

In order to statistically analyze the results, ANOVA was performed. Process variables having p-value less than 0.05 are considered significant terms for the requisite response characteristics. The insignificant parameters were pooled using backward elimination method. The pooled version of ANOVA for MRR (Table 3) indicates that (A), (B), (C), (D), the interaction terms (BD) and the quadratic terms (B^2, D^2) are significant parameters affecting MRR.

Table 3: Pooled ANOVA for MRR

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F	
Model	690.73	7	98.68	31.31	<0.0001	Significant
A	373.97	1	373.97	116.65	<0.0001	
B	36.12	1	36.12	11.46	0.0028	
C	46.97	1	46.97	14.90	0.0009	
D	7.92	1	7.92	2.51	0.1278	
B^2	171.63	1	171.63	54.45	<0.0001	
D^2	17.22	1	17.22	5.46	0.0294	
BD	18.06	1	18.06	5.73	0.0261	
Residual	66.19	21	3.15			
Lack of Fit	49.30	17	2.90	0.69	0.7409	Not significant
Pure Error	16.89	4	4.22			
Cor Total	756.92	28				
Std. Dev	1.78			R-Squared	0.9126	
Mean	9.57			Adj R-Squared	0.8834	
C.V.	18.55			Pred R-Squared	0.8127	
PRESS	141.79			Adeq Precision	21.747	

- The Model F-value of 31.31 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, B2, D2, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
- The "Lack of Fit F-value" of 0.69 implies the Lack of Fit is not significant relative to the pure error. There is a 74.09% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.
- The "Pred R-Squared" of 0.8127 is in reasonable agreement with the "Adj R-Squared" of 0.8834. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 21.747 indicates an adequate signal. This model can be used to navigate the design space.

By using table 3, the regression equation for the MRR as a function of four input process variable was developed from the software (RSM) and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

$MRR = 10.98+5.58*Ip + 1.73*Ton - 1.98*Toff - 0.81*TS - 4.99*Ton^2 + 1.58*TS^2 - 2.13*Ton*TS$

ANOVA for overcut

The pooled version of ANOVA for overcut (Table 4) indicates that (A), (B), (C), (D), the interaction terms (BD) and the quadratic terms (B^2) are significant parameters affecting MRR.

Table 4: Pooled ANOVA for Overcut

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob>F	
Model	154.11	6	25.69	23.96	<0.0001	Significant
A	83.90	1	83.90	78.28	<0.0001	
B	9.36	1	9.36	8.74	0.0073	
C	9.01	1	9.01	8.41	0.0083	
D	1.42	1	1.42	1.33	0.2619	
B^2	42.27	1	42.27	39.43	<0.0001	
BD	8.15	1	8.15	7.60	0.0115	
Residual	23.58	22	1.07			

Lack of Fit	20.41	18	1.13	1.43	0.3967	Not significant
Pure Error	3.17	4	0.79			
Cor Total	177.69	28				
Std. Dev	1.04		R-Squared	0.8673		
Mean	4.78		Adj R-Squared	0.8311		
C.V.	21.67		Pred R-Squared	0.7561		
PRESS	43.35		Adeq Precision	18.656		

- The Model F-value of 23.96 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, B2, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
- The "Lack of Fit F-value" of 1.43 implies the Lack of Fit is not significant relative to the pure error. There is a 39.67% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.
- The "Pred R-Squared" of 0.7561 is in reasonable agreement with the "Adj R-Squared" of 0.8311. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 18.656 indicates an adequate signal. This model can be used to navigate the design space.

By using table 4, the regression equation for the overcut as a function of four input process variable was developed from the software (RSM) and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

$$\text{Overcut} = -6.86869+0.17628*Ip +2.77297*Ton -0.21667*Toff +1.79708*TS -0.15320*Ton^2 -0.35688*Ton*TS$$

Multi Response Optimization

Multi response optimization was carried out using desirability function in conjunction with RSM to overcome the problem of contradictory responses of single response optimization. All possible multi characteristics models have been developed. Goals and limits were established for each response in order to accurately determine their impact on overall desirability. A maximum or minimum level is provided for all response characteristics which are to be optimized. Weights are assigned in order to give extra emphasis to upper or lower bounds or to emphasize a target value. Figures shows the ranges of all input and output variables. Table 5 show the desirability of material removal rate and overcut.

Table 5: Range of Input Parameters and MRR and Overcut for Desirability

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Ip	is in range	5	35	1	1	3
Ton	is in range	2	10	1	1	3
Toff	is in range	2	10	1	1	3
TS	is in range	1	3	1	1	3
MRR	maximize	1.14	21.7	1	1	3
Overcut	minimize	1.04	10.05	1	1	3

By applying the multi response optimization with RSM, we get optimal solution shown in the table 6.

Table 6: Set of Optimal Solutions for MRR and Overcut

Number	Ip	Ton	Toff	TS	MRR	Overcut	Desirability	
1	33.84	10	5.10	2	11.958	5.12	0.536	Selected
2	34.99	2	2.40	1	11.881	4.79	0.552	
3	35	2	2.86	1	11.660	4.69	0.551	
4	32.47	2.19	2.03	1	11.772	4.76	0.551	
5	32.63	2	2	1	11.126	4.51	0.546	

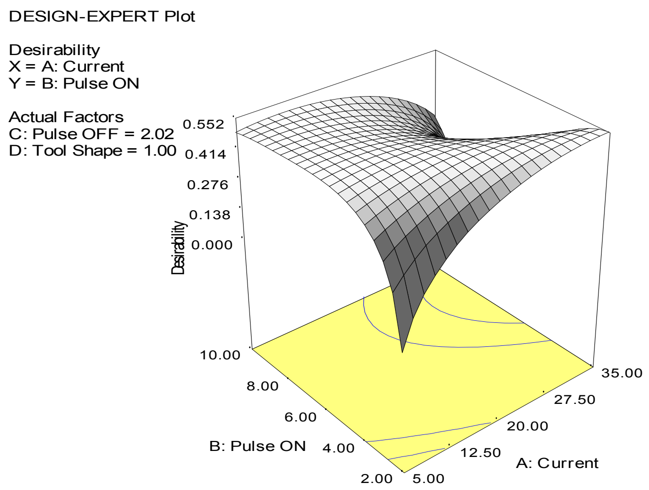

Fig 1: Desirability Graph in between Pulse On and Current for both MRR & overcut

The Figure 1 shows a plot of desirability function distribution of both material removal rate and overcut according to current and pulse on time. It can be visualized that high level of current and middle level of pulse on time favour of high material removal rate and lower overcut.

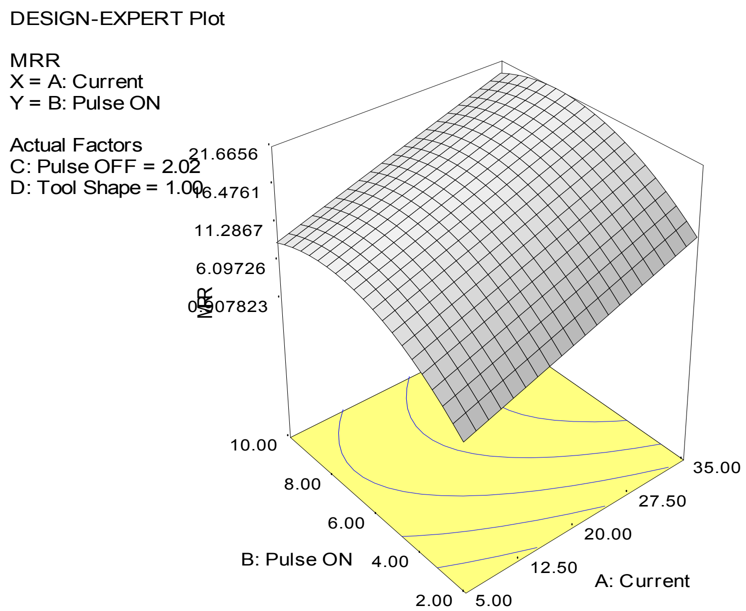

Fig 2: Graph in between Pulse On and Current for MRR

The Figure 2 shows a plot of optimization of material removal rate between current and pulse on time. It can be visualized that high level of current and high level of pulse on time favour of high material removal rate.

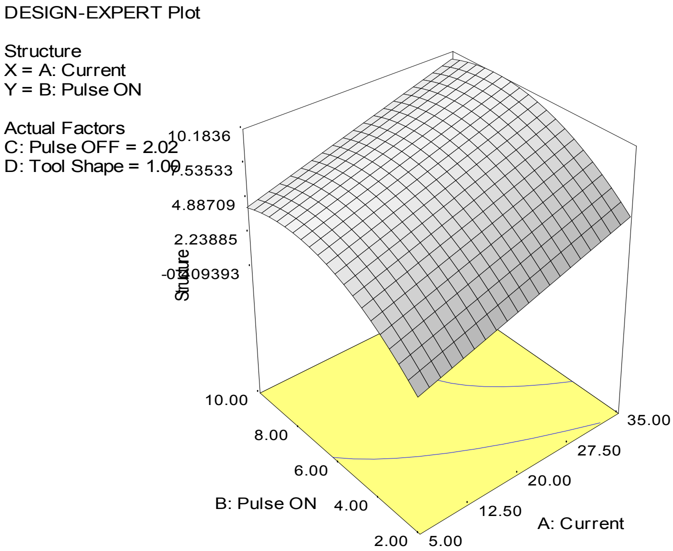

Fig 3: Graph in between Pulse On and Current for Overcut

The Figure 3 shows a plot of optimization of overcut between current and pulse on time. It can be visualized that low level of current and low level of pulse on time favour of lower overcut.

Ram Function and Bar Graph

The ramp function graph and bar graph drawn using Design Expert 6, show the desirability for MRR and overcut. Figure 4 shows the ramp function graph of desirability for MRR and overcut. The dot on each ramp reflects the factor setting or response prediction for those response characteristics. The height of the dot shows how much desirable it is. A linear ramp function is created the low value and the goal or the high value and the goal as the weight for each parameter was set equal to one.

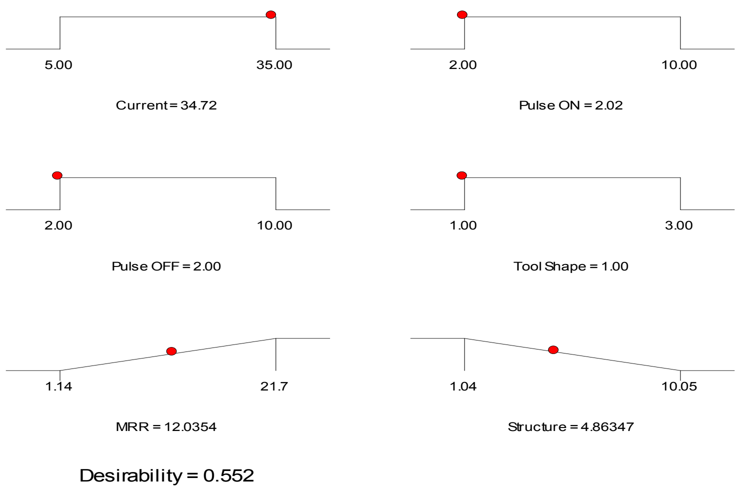

Fig 4: Ramp Function Graph of Desirability for MRR and Overcut

The Figure 5 shows the Bar graph of overall desirability function of the input parameters and responses (MRR and Overcut). Desirability varies from 0 to 1 depending upon the closeness of the response towards target. The bar graph shows how well each variable satisfies the criterion.

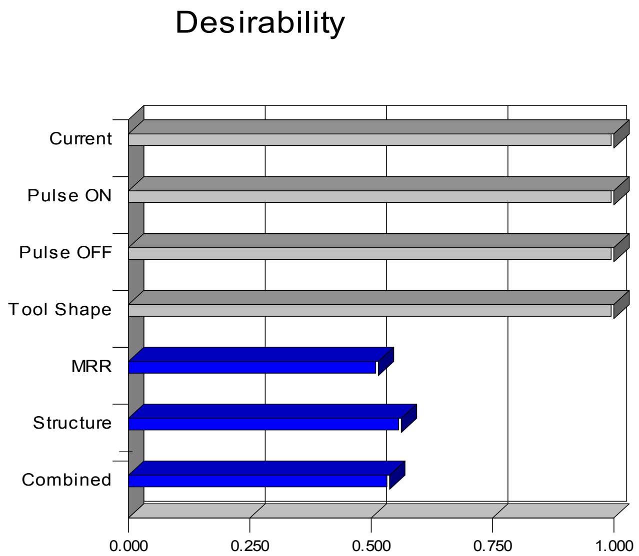

Fig 6: Bar Graph of Desirability for MRR and Overcut

IV. Conclusions

In present work, the experimental study during the machining of Die Steel on EDM. A total 29 experiments were conducted to identify the best possible machining characteristics to maximize the MRR and minimize the Overcut. The conclusions were as follows.

1. From the experimental data of RSM, empirical model were developed and the confirmation experiments were performed, which were found within 95% confidence interval.
2. MRR =10.98+5.58*Ip + 1.73*Ton -1.98*Toff -0.81*TS -4.99*Ton^2 +1.58*TS^2 -2.13*Ton*TS
3. Overcut = -6.86869+0.17628*Ip +2.77297*Ton -0.21667*Toff +1.79708*TS -0.15320*Ton^2 -0.35688*Ton*TS
4. Desirability function in combination with response surface methodology has been used for single response optimization. Optimal setting for MRR are 35Amp IP, 7.5µs Ton, 2.01µs Toff, and cylindrical shape of electrode. Optimal set for overcut are 7.62Amp IP, 2.26µs Ton, 7.98µs Toff, and hexagonal shape of electrode.
5. Optimal setting for multi response characteristics means for both MRR and Overcut are 33.84Amp IP, 10µs Ton, 5.10µs Toff, and hexagonal shape of electrode.

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