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Optimization of EDM parameters using Response Surface Methodology for EN31 Tool Steel Machining

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Abstract— The present work demonstrates the optimization process of material removal rate (MRR) of electrical discharge machining (EDM) by RSM (Response Surface Methodology). The work piece material was EN31 tool steel. The pulse on time, pulse off time, pulse current and voltage were the control parameters of EDM. RSM method was used to design the experiment using rotatable central composite design as this is the most widely used experimental design for modeling a second-order response surface. The process has been successfully modeled using response surface methodology (RSM) and model adequacy checking is also carried out using Minitab software. The second-order response models have been validated with analysis of variance. Finally, an attempt has been made to estimate the optimum machining conditions to produce the best possible responses within the experimental constraints.

Index Terms— Electrical discharge machining; EDM, Material removal rate; MRR, Response Surface Methodology; RSM, Rotatable central composite design.

I. INTRODUCTION

Technologically advanced industries like aeronautics, automobiles, nuclear reactors, missiles, turbines etc., requires materials like high strength temperature resistant alloys which have higher strength, corrosion resistance, toughness, and other diverse properties. With rapid development in the field of materials it has become essential to develop cutting tool materials and processes which can safely and conveniently machine such new materials for sustained productivity, high accuracy and versatility at automation. Consequently, non-traditional techniques of machining are providing effective solutions to the problem imposed by the increasing demand for high strength temperature resistant alloys, the requirement of parts with intricate and compacted shapes and materials so hard as to defy machining by conventional methods.

Electrical Discharge Machining is a non-traditional machining technique, which is widely used to produce finish parts through the action of an electrical discharge of short duration and high current density between the tool and work piece. The tool and the work piece are free from the physical contact with each other. Generally, the EDM is used for machining of electrical conductive materials in the presence of a dielectric fluid. These are submersed in a dielectric liquid such as kerosene or deionized water. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage. The electrical discharge machining process is widely used in the aerospace, automobile, die manufacturing and plastic mould industries to machine hard metals and its alloy [1]. The basic principle in EDM is the conversion of electrical energy into thermal energy through a series of discrete electrical discharges occurring between the electrode and work piece immersed in the dielectric fluid. The insulating effect of the dielectric is important in avoiding electrolysis of the electrodes during the EDM process. A spark is produced at the point of smallest inter-electrode gap by a high voltage, overcoming the strength dielectric breakdown strength of the small gap between the cathode and anode at a temperature in the range of 8000 to 12,000 °C. Erosion of metal from both electrodes takes place there. The numerical control monitors the gap conditions (voltage and current) and synchronously controls the different axes and the pulse generator. The dielectric liquid is filtrated to remove debris particles and decomposition products [2]. The prediction of optimal machining conditions for good surface finish plays a very important role in process planning. Speeding and Wang [3] have attempted to optimize the process parametric combinations by modeling the process using ANN and characterize the surface in wire electrical discharge machining (WEDM) on AISI 420 through time series techniques. Zhang et al. [4] have investigated the effects on material removal rate, surface roughness and diameter of discharge points in electro-discharge machining (EDM) on ceramics. From the experimental results, they have shown that the material removal rate, surface roughness and the diameter of discharge point all increase with increasing pulse-on time and discharge current. Tsai and Wang [5] have established a semi-empirical model of surface finish on work for various materials (three different grades of steel)

in electrical discharge machining and the parameters of the model viz. peak current, pulse duration, electric polarity and properties of materials have been fitted based on the experimental data using Taguchi method. It is seen that the developed model is dependent on work and tool materials. Singh et al. [6] have developed a model for multi-response optimization of process parameters viz. metal removal rate, tool wear rate, taper, radial overcut and surface roughness on electrical discharge machining of Al-10%SiCp composites. Yih-fong and Fu-chen [7] have presented an approach for optimizing high-speed electrical discharge machining (EDM) using Taguchi methods. They have concluded that the most important factors affecting the EDM process robustness have been identified as pulse-on time, duty cycle, and pulse peak current. Fig. 1 shows Fishbone diagram showing parameters affecting MRR.

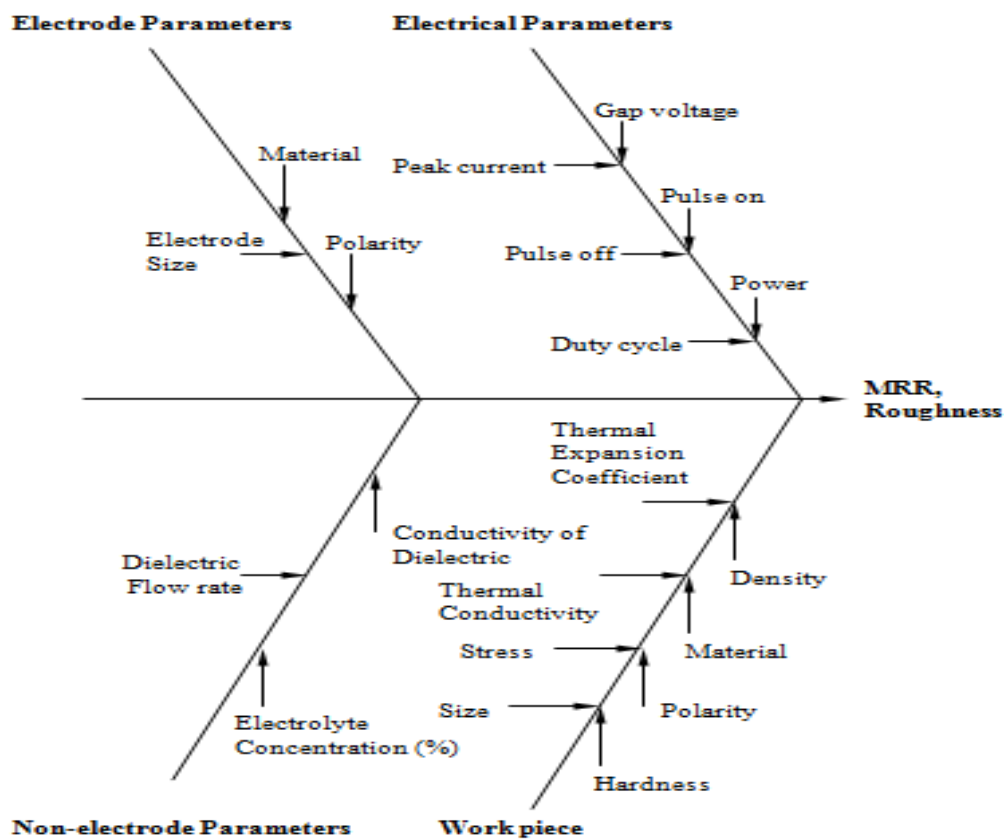


Fig 1. Fishbone diagram showing parameters affecting MRR

The objective of this paper is to study the influence of machining parameters of EDM on EN 31 tool steel using electrolyte copper for and maximizing MRR characteristics. The second order mathematical models in terms of machining parameters are developed for MRR prediction using response surface methodology (RSM) on the basis of experimental results.

II. EXPERIMENTATION AND MEASUREMENT OF RESPONSE

The design of experiments technique is a very powerful tool, which permits to carry out the modeling and analysis of the influence of process variables on the response variables. Improving the MRR and surface quality are still challenging problem that restrict the expanded application of the technology. Semi-empirical models of MRR for various work piece and tool electrode combinations have been presented by various researchers. The influence of pulse current, pulse time, duty cycle, open circuit voltage and dielectric flushing pressure over the MRR and surface roughness on EN 31 tool steel have also been studied. The optimum processing parameters are very much essential to boost up the production rate to a large extent and shrink the machining time, since these materials, which are processed by EDM are costly and the process is very expensive too.

The rotatable central composite design is the most widely used experimental design for modeling a second-order response surface. A design is called rotatable when the variance of the predicted response at any point depends only



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on the distance of the point from the center point of design. Table I shows the components of central composite second order rotatable design.

Variable (K)	Fractional Points (2^k)	Star Point (2k)	Centre Point (n)	Total (N)	Value of α
3	8	6	6	20	1.682
4	16	8	7	31	2.000
5	16	10	6	32	2.000
6	32	12	9	53	2.378

Table I. Components of Central Composite Second Order Rotatable Design [8]

As the number of variables is 4, a total of 31 experiments were planned for this investigation.

Experiments were carried out using CNC EDM (EMT 43) Electronica die sinking machine. Table II shows the specification of die sinking EDM machine.

MACHINING CONDITIONS	
Machine Used	CNC EDM (EMT 43) (Electronica)
Electrode	Electrolytic Copper (99.9% Purity)
Electrode Polarity	Positive
Work piece	Oil Hardened Non Shrinking Steel (48 – 50 R _C)
Dielectric	EDM Oil

Table II. Specifications of die sinking EDM machine

EN 31 Tool Steel block of 22mmx 22mmx15mm size has been used as a work piece material for the present experiments. The chemical composition and mechanical properties of the work-piece materials are (weight %):Carbon: 1.07, Manganese: 0.58, Silicon: 0.32, Phosphorous: 0.04, Sulphur: 0.03, Chromium: 1.12, Ferrous: 96.84 An electrolytic pure copper with 25 mm X 25 mm is used as a tool electrode (positive polarity).The machining parameters and their levels are shown in Table III.

Variable	Coding	Level		
		1	2	3
Pulse On (T_{on}) in μs	A	200	300	400
Pulse Off (T_{off}) in μs	B	1800	1700	1600
Discharge Current (I_p) in A	C	8	12	16
Voltage (V) in V	D	40	60	80

Table III. Different variables used in the experiment and their levels



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The parameter MRR is selected as response variable, which refers to the machining efficiency of the EDM process and defined as follows:

$$\text{MRR (gm/min)} = \frac{W_i - W_f}{t}$$

Where, W_i = Initial weight of work piece material (gms), W_f = Final weight of

work piece material (gms), t = Time period of trials in minutes

The work piece is weighed before and after each experiment using an electric balance to determine the value of MRR. For efficient evolution of the EDM process, the larger MRR is regarded as the best machining performance.

III. METHODOLOGY

In statistics, Response surface methodology (RSM) investigates the interaction between several illustrative variables and one or more response variables. Box and Draper [9] were introducing RSM in 1951. The most important purpose of RSM is to use a series of designed experiments to attain an optimal response. A second-degree polynomial model is used in RSM. These models are only an approximation, but used because such a model is easy to estimate and apply, even when little is known about the process. The process of RSM includes designing of a series of experiments for sufficient and reliable measurement of the response and developing a mathematical model of the second order response surface with the best fittings. Obtaining the optimal set of experimental parameters, thus produce a maximum or minimum value of the response. The Minitab Software was used to analyze the data [10]

IV. RESULT AND DISCUSSIONS

Using the experimental results for MRR (Table IV), response surface model is developed and analysis of variance (ANOVA) for the adequacy of the model is then performed in the subsequent step. The F ratio is calculated for 95% level of confidence.

Term	Coefficient	SE Coefficient	T	P
Constant	0.22752	0.00508	44.787	0
A	0.000681	0.002744	0.248	0.807
B	0.053207	0.002744	19.393	0
C	0.096158	0.002744	35.049	0
D	-0.0431	0.002744	-15.71	0
A*A	-0.00201	0.002513	-0.799	0.436
B*B	-0.00335	0.002513	-1.331	0.202
C*C	0.012858	0.002513	5.116	0
D*D	0.01777	0.002513	7.07	0
A*B	-0.00214	0.00336	-0.636	0.534
A*C	0.00251	0.00336	0.747	0.466
A*D	0.000303	0.00336	0.09	0.929
B*C	0.021314	0.00336	6.343	0
B*D	-0.013	0.00336	-3.868	0.001
C*D	-0.01826	0.00336	-5.433	0
S = 0.0134406		PRESS = 0.0166486		
R-Sq = 99.21%		R-Sq(pred) = 95.46%		R-Sq(adj) = 98.52%

Table IV. ANOVA table for MRR (before elimination) Estimated Regression Coefficients for MRR.

After eliminating the non-significant terms, the final response equation for MRR is given as follows:



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$$\text{MRR} = 0.222579 + (0.000681 \times T_{\text{on}}) + (0.053207 \times T_{\text{off}}) + (0.096158 \times I_p) - (0.043101 \times V) + (0.013372 \times T_{\text{on}}^2) + (0.018285 \times V^2) + (0.021314 \times T_{\text{off}} \times I_p) - (0.012999 \times T_{\text{off}}) - (0.018288 \times I_p \times V)$$

The final model is tested for variance analysis (F-test) and indicates that the adequacy of the test is established which are justified with F-values. For the analysis the data, the checking of goodness of fit of the model is very much required. The model adequacy checking includes the test for significance of the regression model, test for significance on model coefficients, and test for lack of fit. For this purpose, analysis of variance (ANOVA) is performed. Table V shows the ANOVA for the response, MRR. The fit summary recommends that the quadratic model is statistically significant for analysis of MRR.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Regression	9	0.363588	0.363588	0.040399	244.87	0
Linear	4	0.334449	0.334449	0.083612	506.8	0
Square	2	0.013834	0.013834	0.006917	41.93	0
Interaction	3	0.015304	0.015304	0.005101	30.92	0
Residual Error	21	0.003465	0.003465	0.000165		
Lack-of-Fit	15	0.003465	0.003465	0.000231		
Pure Error	6	0	0	0		
Total	30	0.367052				

Table V. Analysis of Variance for MRR

The normal probability plot of residuals for MRR is illustrated in Fig 2. It is expected that data from experiments form a normal distribution. It reveals that the residual fall on a straight line, implying that the errors are spread in a normal distribution. Here a residual means difference in the observed value (obtained from the experiment) and the predicted value or fitted value. This is also, confirmed by the variations between the experimental results and model predicted values analyzed through residual graphs, and are presented in Fig 3.

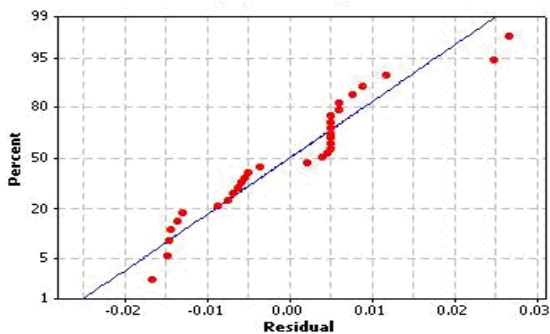


Fig 2. Normal probability plot

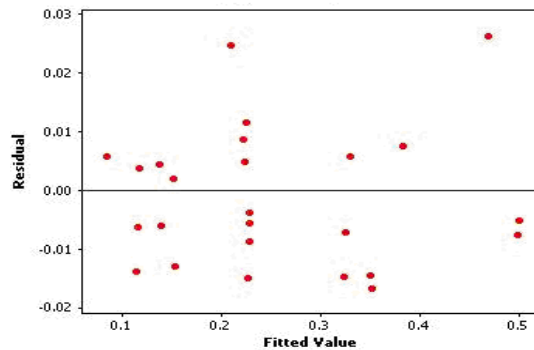


Fig 3. Residual plot

Main Effects Plot for MRR

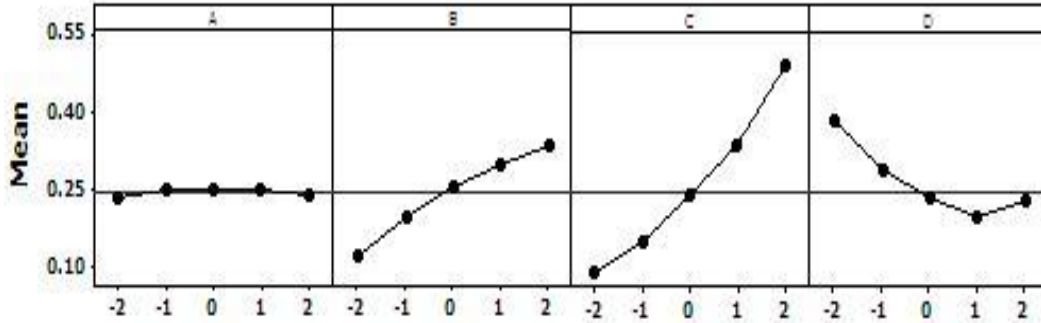


Fig 4. Main Effects plot

From this main effects plot, Figure 4 it is clear that the parameters pulse off and current have highest inclination, so these are most significant but pulse on and voltage are nearly horizontal, so these are non-significant.

The parametric analysis has been carried out to study the influences of the input process parameter such as T_{on} , T_{off} , I_p and V on the process response, MRR during die-sinking EDM process. Contour plots and three-dimensional response surface plots are formed based on the quadratic model to evaluate the variation of response. The plots are shown in Figures 5-10. These plots can also give further assessment of the correlation between the process parameters and response as under:

1. MRR increases with increase in I_p and T_{on} . This is due to higher spark energy from high temperature. (Figure 5)
2. MRR decreases with increase in T_{off} .
3. Increase in applied voltage also increase MRR. (Figure 7)

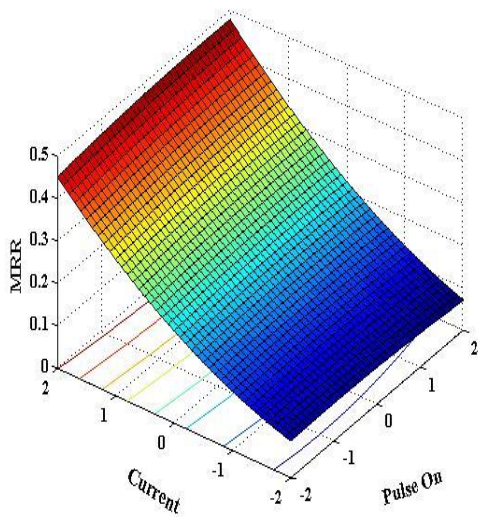


Fig 5. Variation of MRR according to change of I_p and T_{on}
Hold value: $T_{off}=1700(\mu s)$, $V=60$

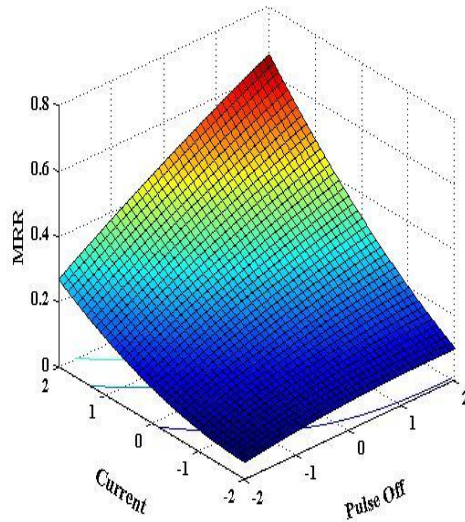


Fig 6. Variation of MRR according to change of I_p and T_{off}
Hold value: $T_{on}=300(\mu s)$, $V=60$



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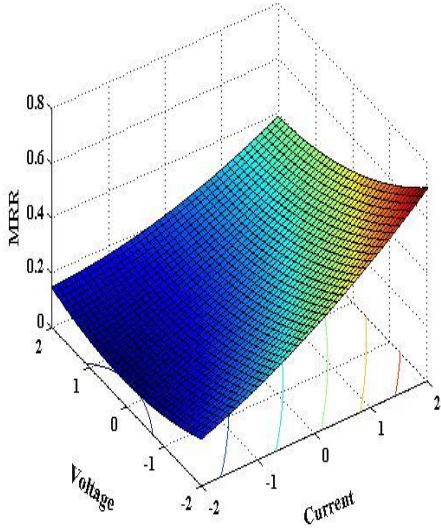


Fig 7. Variation of MRR according to change of voltage and current
Hold on Values: $T_{on}=300(\mu s)$, $T_{off}= 1700(\mu s)$

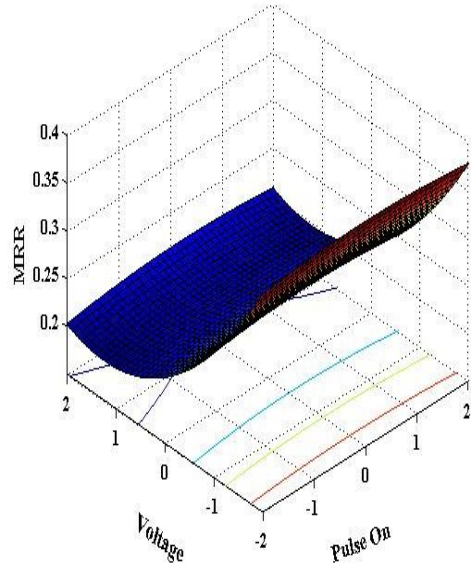


Fig 8. Variation of MRR change of voltage and
Hold value: $I_p = 12A$, $T_{off}=1700(\mu s)$

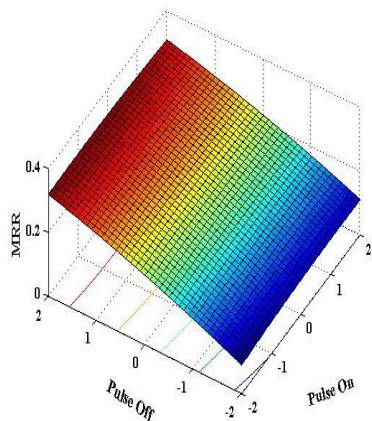


Fig 9. Variation of MRR according to change of T_{off} and T_{on}
Hold value: $I_p= 12A$ $T_{on}=300(\mu s)$

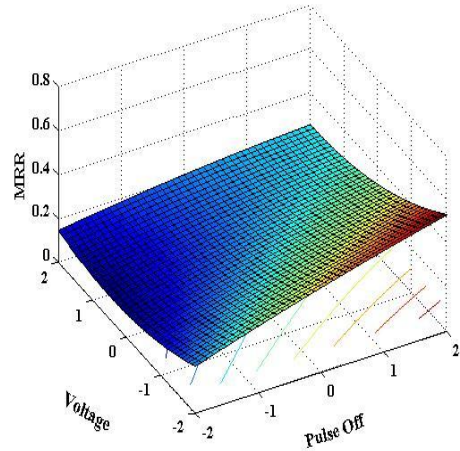


Fig 10. Variation of MRR according to change of T_{off} and voltage
Hold value: $V=60$, $I_p= 12A$

To check the developed model one confirmation test is carried out at the mid-levels of the process parameters. Table 4.5 shows the result of the confirmation run for MRR. It is observed that the calculated error is small (about 2%) This confirms the reproducibility of experimental conclusion.

$T_{on}(\mu s)$	$T_{off}(\mu s)$	$I_p (A)$	V (Volt)	MRR(gm/min)		
				Experimental	Model Predicted	error (%)
300	1700	12	60	0.22752	0.222579	2.17

Table VI. Conformation test result and comparison with predicted result as per model



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Finally an optimum condition is obtained from RSM with an objective of maximum MRR within the experimental range and the levels of the process parameters are Pulse on 500 μ s, Pulse off 1500 μ s, Current 20 A and Voltage 60 V.

V. CONCLUSION

Experimental investigation on electrical discharge machining of EN 31 tool steel is performed with a view to correlate the process parameters with the responses for MRR. The process has been successfully modeled using response surface methodology (RSM) and model adequacy checking is also carried out. The second-order response models have been validated with analysis of variance. Finally, an attempt has been made to estimate the optimum machining conditions to produce the best possible response within the experimental constraints. This study can help researchers and industries for developing a robust, reliable knowledge base and early prediction of MRR without experimenting with EDM process for EN 31 tool steel.

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