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Optimization of Process Parameters for Wire Electrical Discharge Machining of High Speed Steel using Response Surface Methodology

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Abstract – Wire EDM is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in wire EDM is treated as challenging one because improvement of more than one performance measures viz. Metal removal rate (MRR), surface finish and kerf width are sought to obtain precision work. Wire EDM is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill or other cutting tools. In this research paper, the machining of High Speed Steel (HSS) material using Wire Electric Discharge Machining (WEDM) with Brass as a wire electrode has been carried out. The pulse on time, pulse off time and servo voltage were selected as control process parameters of Wire EDM. Response Surface Method (RSM) was applied to determine optimized process parameter to maximize Material Removal Rate (MRR) and minimize Surface Roughness (Ra). The results were verified by comparing the experimental value with predicted one and regression equation was used to predict the performance parameter value for the optimal combinations. The effect of process parameters on MRR and Ra was found by using Analysis of Variance (ANOVA). The parameter analysis has been carried out to study the influences of the input process parameter such as Ton, Toff and SV on the process responses such as MRR and Ra.

Keywords – Wire Electric Discharge Machining (WEDM), Material Removal Rate (MRR), Surface Roughness (Ra), Response Surface Method (RSM), HSS material, Analysis of Variance (ANOVA).

I. INTRODUCTION

Wire Electrical Discharge Machining (Wire EDM) was first introduced to the manufacturing industry in late 1960's. By 1975, its popularity was rapidly increasing, as the processes and its capabilities were better understood by the industry. It was only towards the end of 1970's, when Computer Numerical Control (CNC) system was introduced into Wire EDM that brought about a major evolution of the manufacturing process. As a result, the broad capabilities of the Wire EDM process were extensively exploited for any through hole machining application owing to the wire, which has to pass through the part to be machined.

Its broad capabilities have allowed it to encompass production in aerospace and automotive industries and virtually all areas of conductive material machining. This is because Wire EDM provides the best alternative or sometimes the only alternative, for machining conductive, exotic and high strength and temperature resistive materials with the scope of generating intricate shapes and profiles.

Wire Electric discharge machining (EDM) is a process of repetitive sparking cycles. A series of electrical pulses generated by the pulse generator unit is applied between the work piece and the traveling wire electrode. In the event of spark discharge, there is a flow of current across the wire electrode - work piece gap. The energy content of a single spark discharge can be expressed as a product of pulse on time x peak current. Energy contained in a tiny spark discharge removes a Fraction of work piece material. Large number of such time spaced tiny discharges between the work piece and wire electrode causes the electro-erosion of the work piece material.

Wire cut EDM machine puts impulse voltage between electrode wire and work piece through impulse source, controlled by servo system, to get a certain gap, and realize impulse discharging in the working liquid between electrode wire and work piece. Numerous tiny holes appear due to erosion of impulse discharging and therefore get the needed shape of work piece. The Wire EDM experimental Set Up was shown in Figure 1.

In Wire EDM the most important performance measures such as Metal Removal Rate (MRR) and Surface Roughness (Ra) were depend on machining parameters or input process parameter such as discharge current, pulse on time, pulse off time, wire speed, wire tension, servo voltage and dielectric flow rate. Among these input process parameters Pulse on time, pulse off time and servo voltage have been considered for experimental purpose, as they are the most significant control factors for both maximization of MRR and minimization of Ra.

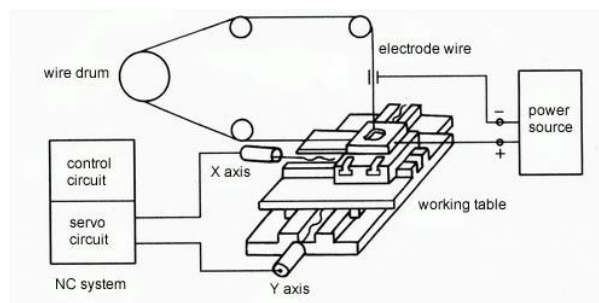


Figure1 Wire EDM experimental Set Up

As there are too many adjustable input process parameters to obtain maximum MRR and minimum Ra, it is very difficult to set process parameter according to the requirement of performance measures. To solve this difficulty, a simple but reliable method based on statistically designed experiments is suggested for investigating the effects of various process parameters on MRR and Ra and determine optimal process settings. There are several optimizing techniques available and among them Response Surface Methodology (RSM) is very efficient, powerful experimental design tools which uses simple, effective and systematic approach for deriving of the optimal machining parameters.

In the present work, Response Surface Method (RSM) was applied to determine optimized process parameter to maximize Material Removal Rate (MRR) and minimize surface roughness (Ra). The results were verified by comparing the experimental value with predicted one and regression equation was used to predict the performance parameter value for the optimal combinations. The parameter analysis has been carried out to study the influences of the input process parameter on the process responses by using surface plot.

II. METHODOLOGY

A. Machine Specification and Material

The experiments were carried out on a Wire EDM machine (Ecocut Wire EDM) to measure MRR value and Mitutoyo Surface Roughness Tester was used to measure Ra value.

The Wire EDM machine tool has following specifications:

X Axis Table Travel	: 250 mm
Y Axis Table Travel	: 350 mm
Z Axis Travel	: 200 mm
Max. work piece size	: 575 X 835 X 200 mm
Max. Work piece wt.	: 275 Kg
Main table feed rate	: 80 mm/ min
Wire feed rate	: 0 - 10 m / min
Wire guide type	: Diamond closed
Wire electrode diameter	: 0.25mm STD, 0.2mm optional
Input voltage	: 310 V to 467 V line to line. i.e . 180 -- 270 V / phase
Output voltage	: 415 V line to line i.e . 240 V phase to neutral
Voltage correction rate	: 35 V / sec
The de-ionized water is used as dielectric	

The Mitutoyo Surface Roughness Tester has following specifications

Measurement range : 350 μm (-200 μm to +150 μm)
Power system : 2 Way (AC adaptor/rechargeable built in battery).
The sensor movement given to indenter: 4mm

In this present work High Speed Steel (HSS) is used as work piece material due to the reason that HSS cannot be easily machinable by conventional machining techniques as it has high hardness, also it is an important tool material used in industries. Chemical composition of HSS material is represented in Table 1.

Table 1 Composition of the material

Constituents	C	Si	Ma	P	S	Cr	Mo	Ni
% Comp	1.364	1.9616	0.456	0.052	0.046	1.921	0.127	0.065

B. Optimization Techniques

There are several techniques can be used for optimization of process parameter, in this present work Response Surface Methodology (RSM) was used. The concepts of RSM are explained below:

C. Response Surface Methodology (RSM)

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable/performance parameter) which is influenced by several independent variables (input/process parameter). The problem can be approximated as described in smooth functions that improve the convergence of the optimization process because they reduce the effects of noise and they allow for the use of derivativebased algorithms.

In this method if the response is well modeled by a linear function of the independent variables, then the approximating function as per the First order model is,

$$Y_U = b_0 + b_1X_1 + b_2X_2 + \dots + b_iX_i + e \quad (1)$$

If there is curvature in the system, then a polynomial of higher degree must be used and the corresponding second order model is,

$$Y_U = b_0 + \sum_{i=1}^K b_iX_i + \sum_{i=1}^K b_{ii}X_i^2 + \sum_{j>i}^K b_{ij}X_iX_j + \dots + e \quad (2)$$

Where 'i' is the linear coefficient, 'j' is the quadratic coefficient, ' β ' is the regression coefficient, 'k' is the number of studied and optimized factors in the experiment and 'e' is the random error. Analysis of variance (ANOVA) has taken into account in order to estimate the suitability of the regression model.

III. EXPERIMENTATION

A. Selection of Process Parameters and their Levels

For experimental purpose three process parameters such as pulse on time (Ton), pulse off time (Toff) and servo voltage (SV) are selected and are varied during experimentation in three levels, the ranges are found by trial and error method. Table 2 shows levels of process parameters selected. To minimize the effects of other process parameters on performance measure, they are kept constant. Table 3 shows the values of process parameters maintained constant.

Table 2 Levels of process parameters

Process parameter	Levels		
	Level 1	Level 2	Level 3
Ton(μs)	110	115	120
Toff(μs)	30	40	50
SV (V)	15	20	25

Table 3 Values of process parameters maintained constant

Name of parameters	Value	Fixed parameters	
Peak current	12 amps	Wire	0.25mm dia of Brass
Wire feed	7 m/min	Shape of work piece	Rectangular
Wire tension	7 μ N	Thickness of work piece	6mm
Servo feed	2100 mm/min	Work height	8mm

B. Experimental Design using Response Surface Methodology (RSM)

In RSM, L20 orthogonal array was chosen. It consists of 20 rows corresponding to the number of experiments with three columns of process parameters at three levels. The experiments were conducted for each combination of process parameters as per L20 orthogonal array. Cutting speed was measured during each trial in Ecocut Wire EDM machining and is used to calculate MRR, while Surface roughness was measured for each trial in Mitutoyo Surface Roughness tester and is directly used. Face centered central composite design was adopted to design the experiments. Table 4 shows the L20 orthogonal array and experimental results. RSM was used to develop second order regression equation which gives relation between process parameters (T_{ON} , T_{OFF} and SV) and performance measures (MRR or Ra).

In Ecocut Wire EDM machine MRR can be calculated using follow equation:

$$MRR = (\text{Cutting speed}) \times (\text{work height}) \quad (3)$$

Where 'work height' was set in Wire EDM machine slightly larger than work piece thickness

Table 4: L20 orthogonal array and experimental results for RSM

Sl no	Ton (μ s)	Toff (μ s)	SV (V)	Cutting Speed (mm/min)	Work Height (mm)	MRR (mm^2/min)	Surface Roughness Ra (μ m)
1	105	30	15	1.72	8	13.76	2.152
2	115	50	15	2.0599	8	16.4792	2.360
3	115	30	25	3.2358	8	25.8864	2.162
4	105	50	25	0.74	8	5.92	1.623
5	110	40	20	2.3103	8	18.4824	2.288
6	110	40	20	2.3103	8	18.4824	2.288
7	115	30	15	3.77	8	30.16	2.7388
8	105	50	15	0.9142	8	7.3136	1.751
9	105	30	25	1.4012	8	17.216	1.929
10	115	50	25	1.57	8	12.56	1.845
11	110	40	20	2.3103	8	18.4529	2.288
12	110	40	20	2.3103	8	18.4529	2.288
13	105	40	20	1.63	8	13.04	1.780
14	115	40	20	3.5360	8	28.288	2.496
15	110	30	20	2.9402	8	23.5216	2.296
16	110	50	20	1.1287	8	9.0296	2.085
17	110	40	15	2.5543	8	20.4344	2.339
18	110	40	25	2.125	8	17	2.225
19	110	40	20	2.3103	8	18.4824	2.288
20	110	40	20	2.3103	8	18.4824	2.288

IV. RESULTS AND DISCUSSION

A. Main Effects Plots

Figures 2 and 3 show the effect of three process parameters on MRR and Ra respectively, indicating that ‘Ton’ is the most affecting parameter for both MRR and Ra, while ‘Toff’ and ‘SV’ are less significant for both MRR and Ra. Main effects plots are generated based on Analysis of Variance (ANOVA) using MINITAB 16 software.

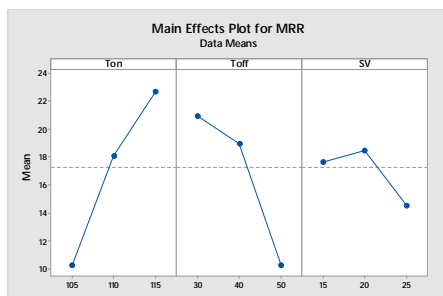


Figure 2: main effects plot for data means of MRR

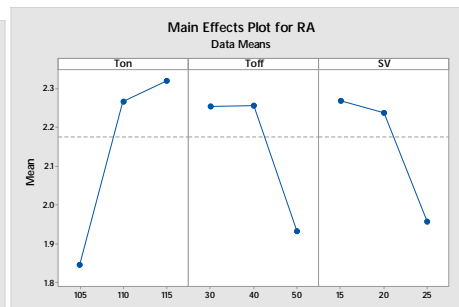


Figure 3: main effects plot for data means of Ra

B. Surface Plots for MRR and Ra

The parameter analysis has been carried out to study the influence of the input process parameters such as Ton, Toff and SV on the process responses (MRR & Ra). Three-dimensional response surface plots are formed based on the quadratic model to evaluate the variation of response. The surface plots are shown in Figures 4(a), 4(b) and 4(c) for MRR and Figure 4(d), 4(e) and 4(f) for Ra. These plots can also provide further assessment of the correlation between the process parameters and response. The surface plots are generated using MINITAB 16 software.

Figure 4(a) shows that MRR increases with the increase of Ton and decrease of Toff. This is due to the reason that with the increase of Ton and decrease of Toff, the interval of electric discharge increases and hence number of sparks which produce higher spark energy and high temperature which also causes roughness to increase as shown in Figure 4(d). Figure 4(b) shows that with the decrease of SV and increase of Ton, MRR increases to a certain value and start to decrease. This is due to the reason that with the increase of Ton discharge will be more and also with decrease of SV the advance of wire or table is more, which results into higher debris. This debris gets deposited on to the work piece and results in unwanted sparks. This causes tool material erosion which results into lesser MRR but debris deposited will also cause increase in the roughness, so after that the value of roughness increases rapidly as shown in Figure 4(e). Further decrease in SV causes wire breakage. Figures 4(c) and 4(f) show that the MRR and Ra increases with decreased Toff. This is due to increase in discharge but decrease in SV causes increase in MRR to a certain value after that it decreases. This is due to the same reason mentioned above.

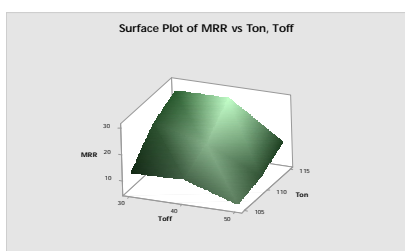


Figure 4 (a)

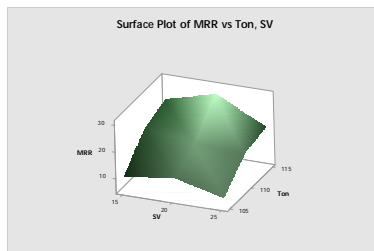


Figure 4 (b)

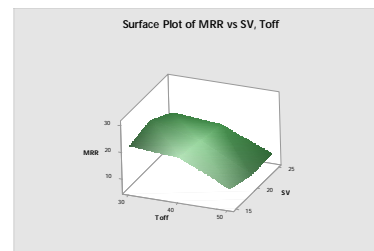


Figure 4 (c)

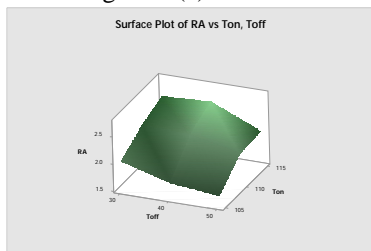


Figure 4 (d)

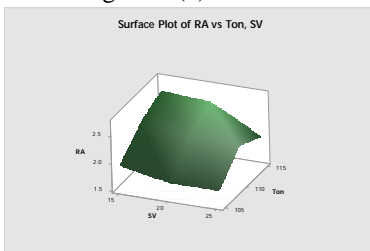


Figure 4 (e)

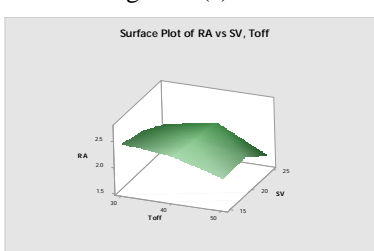


Figure 4 (f)

Figure 4: Surface plot of (a) MRR vs Ton, Toff, (b) MRR vs Ton, SV, (c) MRR vs SV, Toff, (d) Ra vs Ton, Toff (e) Ra vs Ton, SV, (f) Ra vs SV, Toff

C. Optimization using Desirability Approach

Figures 10 and 11 show the optimization plot using desirability approach for maximization of MRR and minimization of Ra respectively. This optimization plots for MRR and Ra are generated using Minitab 16 software.

Desirability approach has been used for finding out the optimum values of the process parameters in order to get the maximum value of MRR and minimum value of Ra. It is clear from Figure 4 that highest value of MRR of 31.4975 mm²/min is obtained for the combination of Ton = 115 μs, Toff = 30 μs and SV = 15 volt. It is clear from the Figure 5 that lowest value of Ra of 1.6228 μm is obtained for the combination of Ton = 105 μs, T_{OFF} = 50 μs and SV = 25 volt. The results obtained are with the composite desirability of 1.000.

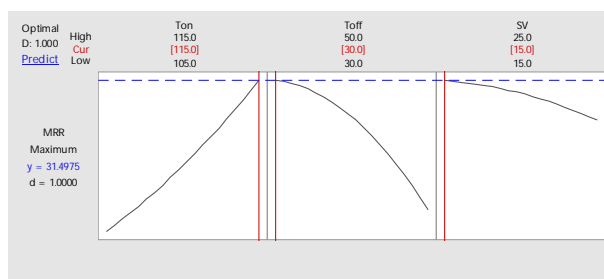


Figure 10: Optimization plot for MRR

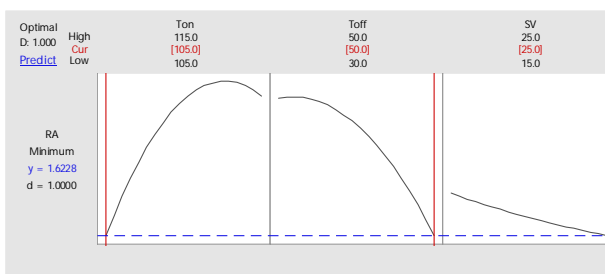


Figure 11: Optimization plot for Ra

D. Regression Analysis

The experimental results were used to develop a mathematical model called as regression equation which is used to express the relation between the process parameters and performance measures (MRR & Ra). MINITAB 16 software was used to determine the co-efficient of mathematical models. The optimal combinations obtained from the analysis of results are verified by conducting the experiments for those combinations. The regression equation used to predict the performance measures value for the optimal combinations of process parameters. Both experimental and predicted values for optimum parameters to get maximum MRR and minimum Ra are shown in Table 5.

For MRR and Ra, regression equations are given in equation 3 and 4 respectively

Table 5: Confirmation experiments for MRR and Ra

Response	Optimized value of input parameter			Predicted	Experimental	% Error
	T _{ON}	T _{OFF}	SV			
MRR	115	30	15	31.497	30.16	4.43
Ra	105	50	25	1.6228	1.623	0.0123

$$\text{MRR} = 191 - 6.95 \text{ Ton} + 6.18 \text{ Toff} + 3.15 \text{ SV} + 0.0461 \text{ Ton} * \text{Ton} - 0.03236 \text{ Toff} * \text{Toff} - 0.0318 \text{ SV} * \text{SV} - 0.0382 \text{ Ton} * \text{Toff} - 0.0213 \text{ Ton} * \text{SV} + 0.0038 \text{ Toff} * \text{SV} \quad (3)$$

$$\text{Ra} = -77.3 + 1.332 \text{ Ton} + 0.0423 \text{ Toff} + 0.353 \text{ SV} - 0.00551 \text{ Ton} * \text{Ton} - 0.000882 \text{ Toff} * \text{Toff} + 0.00025 \text{ SV} * \text{SV} + 0.000042 \text{ Ton} * \text{Toff} - 0.00373 \text{ Ton} * \text{SV} + 0.000378 \text{ Toff} * \text{SV} \quad (4)$$

V. CONCLUSIONS

In this study an attempt was made to determine the values of optimum process parameters to maximize the material removal rate and minimize the surface roughness in Wire EDM.

- A. RSM approach was employed for designing as well as for finding out optimal solution.
- B. It is clear that Pulse on time has greater influence on maximization of MRR and minimization of Ra.
- C. Pulse off time and servo voltage influence the MRR and Ra to a smaller extent.
- D. To maximize the MRR, according to RSM, optimized process parameters are Ton=115 (level 3), Toff=30 (level 1), SV=15 (level 1).
- E. To minimize the Surface roughness, according to RSM, optimized process parameters are Ton=105 (level 1), Toff=50 (level 3), SV=25 (level 3).
- F. The MRR and Ra obtained from RSM analysis are 31.4975mm²/min and 1.6228 μ m respectively.
- G. The predicted and experimental results of MRR and Ra for optimized levels of process parameters obtained are very close to each other. Hence RSM has good agreement towards optimization.
- H. Process parameters for customized values of MRR and Ra can be obtained by solving equation obtained from desirability approach.

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