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Optimization of Wire EDM Parameters for Fabrication of Micro Channels

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***Abstract*—**Wire Electric Discharge Machining (WEDM) is thermal machining process capable of machining very hard electrically conductive material irrespective of their hardness. WEDM is being widely used to machine micro scale parts with the high dimensional accuracy and surface finish. The objective of this paper is to optimize the process parameters of wire EDM to fabricate the micro channels and to calculate the surface finish and material removal rate of micro channels fabricated using wire EDM. The material used is aluminum 6061 alloy. The experiments were performed using CNC wire cut electric discharge machine. The effect of various parameters of WEDM like pulse on time (T_{ON}) with the levels (100, 150, 200), pulse off time (T_{OFF}) with the levels (25, 35, 45) and current (I_P) with the levels (105, 110, 115) were investigated to study the effect on output parameter i.e. Surface Roughness and Material Removal Rate (MRR). Each experiment was conducted under different conditions of pulse on time, pulse off time and peak current. For material removal rate, T_{ON} and I_p were the most significant process parameter. MRR increases with the increase in T_{ON} and I_p and decreases with the increase in T_{OFF}. For surface roughness, T_{ON} and I_p have the maximum effect and T_{OFF} was found out to be less effective.

***Keywords*—**Micro Channels, Wire Electric Discharge Machining (WEDM), Metal Removal Rate (MRR), Surface Finish.

I. Introduction

WIRE EDM works on the principle of conversion of electrical energy into heat energy which melts the material. A spark is produced between the wire electrode (usually smaller than 0.3 mm) and work piece through deionised water (used as dielectric medium surrounding the work piece) and erodes the work piece to produce complex two and three dimensional shapes. This process can be used for any material which is electrically conductive in nature. In this process, metal is removed from the work piece by melting and vaporization due to pulse discharges that occur in a small gap between the work piece and the electrode (wire). It is a novel machining process used for fabrication of a micro-metal hole and can be used to machine hard electrically conductive materials. Wire electrode methods can cut complicated shapes like a wire sawing machine. Normally the wire electrode is brass wire or coated steel wires but in case of thin wires tungsten or molybdenum wires are used. Since we can change the orientation of the wire by controlling the horizontal position of the upper wire guide relative to the lower guide all types of surfaces can be cut.

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Response surface methodology is statistical technique to design the experiment. Response surface methodology is collection of mathematical and statistical technique useful for modeling and analysis of problem which depicts the influence of input variables on the response which is need to optimize. It is an approach to design the experiment. Response surface methodology is used to obtain the mathematical model of the experiment depicting the relation between the input variables and output response. In RSM necessary and useful data is collected in terms of the input variables for the optimization of the response. Then this data is utilized for the design of experiment. Two level factorial or the three level factorial designs is used depending on the number of variable used to conduct the experiments. Higher the number of input variables chosen larger will be the number of experiments to conduct.

Micro channels can be fabricated using different technique such as stereo lithography, wafer bonding technique, electroforming, micro electric discharge machining etc.

Over the past decade many researchers have done immense work to improve the Material removal rate (MRR) using different methods to optimize and improve the material removal rate along with the surface finish. Chaudhary et al. studied the effects of process parameters of WEDM such as T_{ON}, T_{OFF}, I_P, S.V for analysis the material removal rate of EN5 mild steel material using RSM [1]. Son et al. studied the influences of EDM pulse condition on the micro EDM properties. Voltage, current, and on/off time of the pulse were selected for the material removal rate [2]. ESME et al. used factorial design and neural network (NN) for modeling and predicting the surface roughness of AISI 4340 steel [3]. Regression analysis and (ANOVA) method was used to establish the mathematical relation and to determine level of importance between the input and output parameters. Muthu et al. used Grey–Taguchi Method to optimize parameters of WEDM of Incoloy 800 super alloy with for MRR, SF and Kerf [4]. Optimal levels of process parameters were identified using Grey Relational Analysis and Analysis of Variance methods were used. Mir et al. optimized parameters of powder mixed electrical discharge machining of H11 steel using response surface methodology and ANOVA for the surface finish [5]. Phipon and Pradhan used Genetic Algorithm and RSM for the single and multi-objective optimization of micro EDM process [6]. T_{ON}, T_{OFF}, I_P and flushing pressure effect on

TWR and overcut were studied. Singh and Singh used RSM and GA to study the effect of parameter T_{ON}, T_{OFF} and tension and flushing rate on MRR and surface roughness [7]. Lakshmanan and Kumar used RSM and ANOVA to optimize the process parameter like T_{ON}, T_{OFF}, I_P, S.V, for MRR on EDM of EN31 tool steel for MRR [8]. Majhi et al. optimized parameters for MRR, SR, TWR of EDM using GRA, RSM and entropy method [9]. Joshi et al. evaluated the influence of T_{ON}, T_{OFF}, SV on surface roughness of high carbon and high chromium steel using response surface methodology [10].

II. Experimentation

Experiments are designed using the design of Experiments (DOE). Response Surface Methodology (RSM) is used for this design. Three factors are chosen with three different levels for the input parameters to study the effect on the output variables (responses). Central composite design is used. Aluminum 6061 alloy is used as work piece material. Work pieces of 22x22 mm are prepared and micro channels of 0.5x0.5 mm are fabricated on these work pieces using Electronica ELPULS 40ADLX CNC wire cut EDM Machine. Brass wire is used as the electrode material. Surface finish of the micro channels are measured using the Taylor Hobson contact type profilometer having the stylus diameter of 2µm. Material removal rate is calculated using volume of material removal per unit time as shown in (1):

$$MRR = \frac{W_1 - W_2}{t\rho} \quad (1)$$

where, W_1 is weight of work piece before machining, W_2 is weight of work piece after machining, t is time taken to fabricate micro channels, and ρ is the density of aluminium 6061 alloy. The input process parameters along with their three levels considered for final experimentation as given in Table I:

TABLE I
INPUT PARAMETERS AFFECTING FABRICATION PROCESS

Parameters	$-\alpha$	-1	0	1	α	Units
Peak Current (I_p)	65.91	100	150	200	230	Amp
Pulse On Time (T_{ON})	101.5	105	110	115	118.4	μsec
Pulse Off Time (T_{OFF})	18.4	25	35	45	51.81	μsec

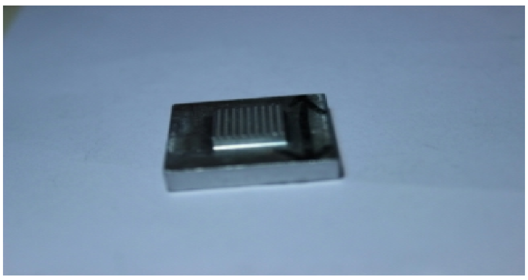

Fig. 1 Fabricated Micro Channels

Experiment designed after applying Design of Experiments (DOE) and coded combinations of process parameters i.e. Pulse on Time (T_{ON}), Pulse off Time (T_{OFF}) and Current (I_p) are shown in Table II along with the measured responses i.e. material removal rate (MRR) and surface roughness (RA). Micro channels of aluminum of size 500µm were prepared on the CNC WIRE CUT EDM. The image of micro channels made on aluminum specimen after wire EDM process is shown in Fig. 1.

TABLE II
CODED COMBINATIONS OF PROCESS PARAMETERS FROM DOE

Order	Run Order	I_p	T_{ON}	T_{OFF}	MRR	Ra
11	1	0	-1.68	0	2.7673	2.5791
18	2	0	0	0	5.3255	3.6091
20	3	0	0	0	5.1364	3.4012
17	4	0	0	0	5.2403	3.0154
7	5	-1	1	1	4.5764	3.1198
5	6	-1	-1	1	2.1438	3.2884
12	7	0	1.68	0	6.4744	3.3613
10	8	1.68	0	0	4.7679	4.1439
4	9	1	1	-1	6.5348	3.978
8	10	1	1	1	3.9923	4.2163
15	11	0	0	0	5.0193	3.609
1	12	1	-1	-1	3.8979	2.5849
16	13	0	0	0	5.3165	3.4014
19	14	0	0	0	5.2741	3.1047
2	15	1	-1	1	3.2714	2.2913
3	16	-1	1	1	4.7185	3.1511
13	17	0	0	-1.68	3.6973	3.245
9	18	-1.68	0	0	3.862	2.6459
6	19	1	-1	1	3.173	2.0142
14	20	0	0	1.68	3.5024	3.0447

TABLE III
ANALYSIS OF VARIANCE FOR METAL REMOVAL RATE

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	24.830	24.830	2.759	30.33	0.000
Linear	3	17.531	16.539	5.513	60.60	0.000
I_p	1	0.323	1.458	1.458	16.03	0.003
T_{ON}	1	14.421	13.957	13.957	153.42	0.000
T_{OFF}	1	2.787	0.855	0.855	9.40	0.012
Square	3	5.619	6.473	2.158	23.72	0.000
I_p*I_p	1	0.793	1.796	1.796	19.74	0.001
T_{ON}*T_{ON}	1	0.282	0.883	0.883	9.70	0.011
T_{OFF}*T_{OFF}	1	4.544	5.180	5.180	56.94	0.000
Interaction	3	1.681	1.681	0.560	6.16	0.012
I_p*T_{ON}	1	0.306	0.717	0.717	7.88	0.019
I_p*T_{OFF}	1	0.463	0.670	0.670	7.36	0.022
T_{ON}*T_{OFF}	1	0.912	0.912	0.912	10.03	0.010
Residual Error	10	0.910	0.910	0.091		
Lack-of-Fit	3	0.824	0.824	0.275	22.35	0.001
Pure Error	7	0.086	0.086	0.012		
Total	19	25.740				

III. Math

A. Analysis of Variance for MRR

The significance of each parameter can be determined using ANNOVA. Any parameter having p value less than or equal to α = 0.05 will be considered significant. It can be seen from Table III that the parameter having less value of p will be more significant. The parameters - Pulse on Time, Pulse off Time, Current have the p value less than α = 0.05 means all these parameters have come out to be significant.

B. Analysis of Variance for Ra

It can be seen from the ANNOVA Table IV that the parameter having less value of p will be more significant. Pulse on time and current have the lowest p value means parameters have maximum effect on Ra but pulse off time value showing less effect on the Ra. Lower value of S = 0.282273 means models better predicts the responses.

TABLE IV
ANALYSIS OF VARIANCE FOR SURFACE FINISH

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	5.561	5.561	0.618	7.75	0.002
Linear	3	2.869	1.461	0.487	6.11	0.012
I_p	1	0.205	0.712	0.712	8.94	0.014
T_{ON}	1	2.562	0.788	0.788	9.88	0.010
T_{OFF}	1	0.102	0.038	0.038	0.48	0.505
Square	3	0.437	0.411	0.137	1.72	0.226
I_p*I_p	1	0.006	0.000	0.000	0.00	0.948
$T_{ON}*T_{ON}$	1	0.304	0.330	0.330	4.14	0.069
$T_{OFF}*T_{OFF}$	1	0.127	0.120	0.120	1.50	0.248
Interaction	3	2.254	2.254	0.751	9.43	0.003
I_p*T_{ON}	1	1.715	1.996	1.996	25.1	0.001
I_p*T_{OFF}	1	0.297	0.214	0.214	2.69	0.132
$T_{ON}*T_{OFF}$	1	0.243	0.243	0.243	3.04	0.112
Residual Error	10	0.797	0.797	0.080		
Lack-of-Fit	3	0.447	0.447	0.149	2.98	0.106
Pure Error	7	0.350	0.350	0.050		
Total	19	6.357				

C. Mathematical Model

Mathematical model developed after applying response surface methodology for material removal rate is given in (2):

$$MRR = 5.22540 + 0.392746I_p + 1.16600T_{on} - 0.294514T_{off} - 0.362748I_p * I_p - 0.254365T_{on} * T_{on} - 0.616114T_{off} * T_{off} - 0.338489I_p * T_{on} - 0.363156I_p * T_{off} - 0.402462T_{on} * T_{off} \quad (2)$$

Mathematical model developed after applying response surface methodology for surface finish is given in (3):

$$SF = 3.35975 + 0.2747544I_p + 0.276978T_{on} + 0.0622322T_{off} - 0.00506475I_p * I_p - 0.155540T_{on} * T_{on} - 0.0936596T_{off} * T_{off} + 0.564719I_p * T_{on} - 0.205376I_p * T_{off} + 0.207493T_{on} * T_{off} \quad (3)$$

D. Residual Plots

Figs. 2 and 3 show that the residuals follow an approximately straight line in normal probability plot and approximate symmetric nature of histogram indicating that the residuals are normally distributed. Since residuals exhibit no clear pattern, there is no error due to time or data collection order.

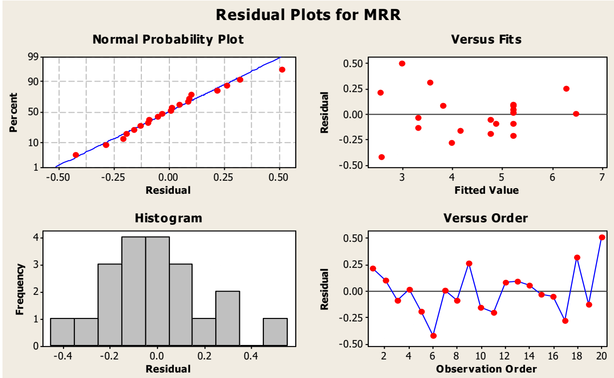

Fig. 2 Residual Plots for Metal Removal Rate

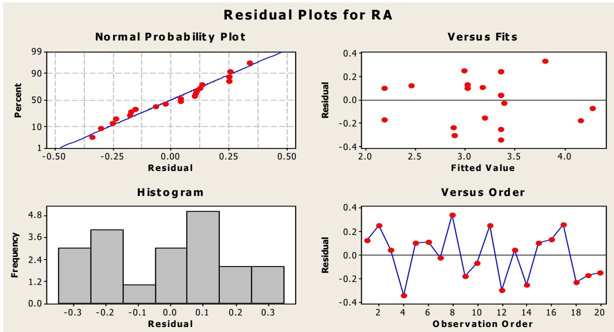

Fig. 3 Residual Plots for Surface Finish

E. Main Effect Plots

Main effect plots for Material Removal Rate (MRR) and Surface Roughness (Ra) are given in Figs. 4 and 5 depicting the variation of data mean for each response at different levels of process parameters.

It can be seen from the main effect plot for MRR, that MRR increases with increase in current and pulse on time and decreases with increase in pulse off time. The reason for this is that discharge energy increases with the increases in pulse on time and decreases with increase in pulse off time. The main effect plot for Ra shows that the value of surface roughness increases with the increase in pulse on time and current. The effect of pulse off time is not very significant.

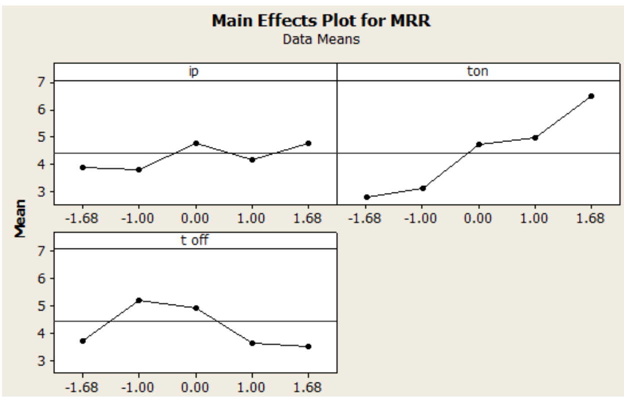

Fig. 4 Main Effect Plots for MRR

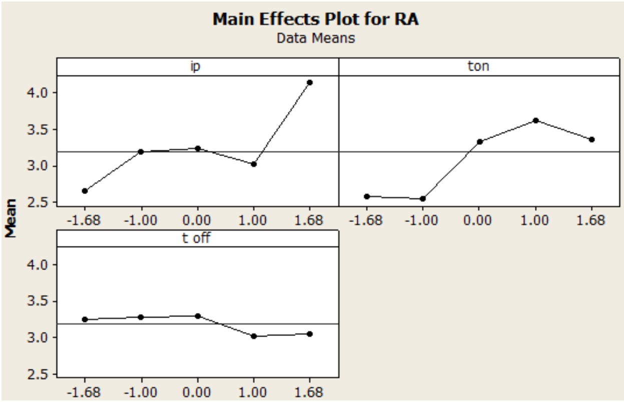

Fig. 5 Main Effect Plots for Surface Finish

IV. Conclusions

In the present research work, effect of three input process parameters (i.e. Current, Pulse on Time and Pulse off Time) on two output parameters (i.e. MRR and Ra) were investigated by response surface methodology approach. The following conclusions can be drawn from the study:

1. For material removal rate T_{ON} and I_p are the most significant process parameter. MRR increases with the increase in T_{ON} and I_p and decreases with the increase in T_{OFF}.
2. For surface roughness T_{ON} and I_p have the maximum effect and T_{OFF} was found out to be less effective.
3. The maximum value of material removal rate comes out to be 6.534 mm^3/min when the levels of parameters were at (I_p = 200, T_{ON} = 115, T_{OFF} = 25) and the minimum value of material removal rate comes out to be 2.1438 mm^3/min when the levels of parameters were at (I_p = 100, T_{ON} = 105, T_{OFF} = 45).
4. The minimum value of surface roughness comes out to be 2.0142 µm when the levels of parameters were at (I_p = 200, T_{ON} = 105, T_{OFF} = 45) and maximum value of surface roughness comes out to be 4.2163 µm when the levels of parameters were at (I_p = 200, T_{ON} = 115, T_{OFF} = 45).

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