International Journal of Engineering Research
Volume No.5 Issue Special 2, pp: 427-431
ISSN:2319-6890)(online),2347-5013(print)
11-12 Feb. 2016

Experimental Investigation of Process Parameters of Submerged Wire EDM for Machining High Speed Steel

A. Chandrakanth[1], Dr. S. Gajanana[2], B. Kshetramohan[3]
[1, 2&3] Department of Mechanical Engineering, MVSR Engineering College, Nadergul, Hyderabad-501510
ackmvsr@gmail.com

Abstract—Wire-EDM as a precision cutting technology is possible to fabricate product of all ranges. In Wire EDM, the conductive materials are machined with a series of electrical discharges (sparks) that are produced between an accurately positioned moving wire (the electrode) and the work piece. High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through insulated dielectric fluid (water). In this current work Pulse on time, Wire tension and Spark gap voltage are the three parameters taken for optimization of MRR. The work piece is HSS M42 Grade and the work tool is brass wire of 0.25 mm dia. The Experiment was conducted in 8 runs using full factorial design and most significant factors are determined using ANOVA. Optimum values of parameters are obtained by using MatLab program (Genetic algorithm). Response surface methodology is also adopted to verify the accuracy of obtained mathematical model.

Keywords— Metal Removal Rate (MRR), High Speed Steel(HSS), Design of Experiments(DOE), Analysis of Variance(ANNOVA).

I. Introduction

Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles WEDM utilizes a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.30 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire, eliminating the mechanical stresses during machining. Several researchers have attempted to improve the performance characteristics namely the surface roughness, cutting speed, dimensional accuracy and material removal rate.

High cost of WEDM machine has forced to operate them as efficiently as possible in order to obtain the required payback. It has been long recognized that cutting conditions such as pulse on time, pulse off time, servo voltage, peak current and other machining parameters should be selected to optimize the economics of machining operations as assessed by productivity, total manufacturing cost per component or other suitable criterion. In the present paper process parameters are optimized using design of experiments.

2. Material and Methodology

Design of experiment is used to optimize the input parameters. In design of experiments, numbers of trails to be conducted are determined by factorial method and design matrix is constructed. After getting design matrix, regression coefficients are calculated. Adequacy of model is tested by fisher test at 5% significance level. Student's t-test is carried out to check the significance of each regression coefficient. The mathematical model is developed by using factorial design of experiments.

The three factors, namely, the Pulse on time, Wire Tension and Spark Gap Voltage are analyzed simultaneously by the main effects with two and three factor interactions.

2.1. Postulation of the mathematical model

A mathematical model is developed considering the factors Pulse on time, Wire Tension and Spark Gap Voltage.

$$Y=b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{23}X_2X_3+b_{13}X_1X_3+b_{123}X_1X_2X_3$$

Where 'y' represents the response, X_1, X_2 and X_3 represent the Pulse on time, Wire Tension and Spark Gap Voltage respectively. b0, b1,b3… are the regression coefficients

2.2 Design of experiment

A two level full factorial design of experiments is adopted for calculating the main and the interaction effects of the three factors at two levels; 2^3= 8 experiments are conducted to fit an equation. The following table represents factors, their levels and other details.

Table 1: Factors and their levels

Factors	Units	Designation		Test levels		Average	Variation interval
		Natural	coded	Low	High		
Pulse on time	µs	Ton	X1	110	130	120	10
Wire tension	N	WT	X2	7	12	9.5	2.5
Spark gap voltage	volts	SV	X3	20	60	40	20

2.3 Decoding of coded linear equation

Decoding of linear equation of Yp= $b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2 + \dots$ is done by substituting the factors $\frac{a_1-Avg_1}{VI_1}$, $\frac{a_2-Avg_2}{VI_2}$… in place of X_1, X_2, … in the above equation. Here a_1, a_2… are natural values of factors. Avg_1, Avg_2, are the

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average values of the factors a_1, a_2… and VI_1 and VI_2 are the variation intervals.

2.4 Development of the model:

Design matrix for a given 2-level and 3-factor is generated and the regression coefficients are calculated.

Here the number of replications for the response i.e.; y_1 and y_2 and average of these is 'y'.

Regression coefficients b_0, b_1, b_2, b_{12}, b_{23} etc are calculated by using the formula

$$b_j = \frac{[\sum_{i=1}^{N} X_{ij} Y_i]}{N}$$

Where N is the number of trials

2.4 Fisher test for Adequacy of model (F-test for 5% significance level)

Variance of Reproducibility = $Sy^2 = \frac{2\Sigma(\Delta y)^2}{N}$

$$\Delta y = (y_1 - y)$$

Variance of adequacy = $S_{ad}^2 = \frac{2\Sigma(y - yp)^2}{DOF}$

Where y_p= predicted response

$y_p = b_0 x_0 [i] + b_1 x_1 [i] + \ldots$

Where DOF =degree of freedom = [N-(k+1)],

N=number of trails, k=number of factors.

$$F_{model} = \frac{S_{ad}^2}{S_y^2}$$

For given values of f_1 and f_2, F-table value is found from Fisher table.

Here f_1= N-(k+1) and f_2=N

If Fmodel<= F-table, model is adequate in linear form from Fisher table

2.5 Student's t-test (for 5% significance level)

When the model is adequate in linear form, then t-test is to be conducted to test the significance of each Regression Coefficient

Standard deviation of each coefficient, $S_{bj} = \sqrt{\frac{(S_y)^2}{N}}$

$$\text{t-ratio} = \frac{|b_j|}{S_{b_j}}$$

For f = N, t value is to be taken from t-table and compared with t-ratio of each regression coefficient. If t-ratio ≥ t-table, corresponding regression coefficient is significant. Non-significant coefficients are to be eliminated from the model to arrive the final form of mathematical model in linear form as $y = b_0 + b_1 X_1 + b_2 X_2 + \ldots\ldots$

2.6 Analysis of Variance (ANOVA):

Analysis of variance is done to find out the percentage contribution of each factor and its relative significance.

Table 2: ANOVA Table

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio
A treatments	SS_A	a-1	$MS_A = \frac{SS_A}{a-1}$	$F_A = \frac{MS_A}{MS_E}$
B treatments	SS_B	b-1	$MS_B = \frac{SS_B}{b-1}$	$F_B = \frac{MS_B}{MS_E}$
Interaction	SS_{AB}	(a-1) (b-1)	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1}$	$F_{AB} = \frac{MS_{AB}}{MS_E}$
Error	SS_E	ab(n-1)	$MS_E = \frac{SS_E}{ab(n-1)}$	
Total	SS_T	ab(n-1)		

'a' and 'b' are the levels of A and B factors

$$SS_A = \frac{\{Sum[X_1[i] * Y_t[i]]\}^2}{Nn}$$

$$SS_T = Sum\{(Y_1[i])^2 + (Y_2[i])^2\}^2 - \frac{\{Sum\{Y_1[i]\}^2}{Nn}$$

Here N=number of trails

SSE= (SSE)-(SSA)-(SSB)……..

Percentage contribution of factor A = $\frac{SS_A}{SS_T} X100$

The experiments were carried out on Wire electrical discharge machine, Model: ULTRA CUT S2 non-conventional machine. The work piece is High Speed Steel material M42 grade of length 52.45mm, diameter 20mm and weight 130.815 gms. The observations were recorded for machining of 50mm length. The cutting conditions were randomized and each experiment run is replicated twice. As per full factorial method $2*2^3$=16 experiments were carried out. The surface roughness of each specimen is measured and MRR is calculated by weighing basis.

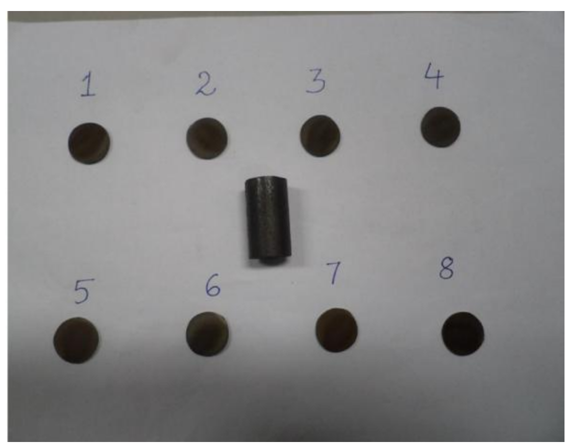

Figure 1: Machined samples

3. Results and Discussion

The following results were obtained in the experiment

Table 3: Observation of the Responses

Experimental order	Pulse on Time (μs)	Wire Tension (N)	Spark gap Voltage (V)	Metal Removal Rate (MRR)
1	**110**	**7**	**20**	0.0280
2	**130**	**7**	**20**	0.0640
3	**110**	**12**	**20**	0.0260
4	**130**	**12**	**20**	0.0631
5	**110**	**7**	**20**	0.0152
6	**130**	**7**	**20**	0.0405
7	**110**	**12**	**20**	0.0145
8	**130**	**12**	**20**	0.0391
9	**110**	**7**	**20**	0.0281
10	**130**	**7**	**20**	0.0641
11	**110**	**12**	**20**	0.0262
12	**130**	**12**	**20**	0.0630
13	**110**	**7**	**20**	0.0151
14	**130**	**7**	**20**	0.0403
15	**110**	**12**	**20**	0.0144
16	**130**	**12**	**20**	0.0390

No. of levels= 2,
No. of Factors (K) = 3
No. of trials (N) = $2^k = 2^3 = 8$

3.1 Development of model for metal removal rate (MRR)

The regression coefficients are calculated and tabulated as follows

Table 4: Regression coefficients of the model

Regression coefficients	Values
b_0	0.0363
b_1	0.0153
b_2	-6.25×10^{-4}
b_3	-8.975×10^{-3}
b_{12}	5×10^{-5}
b_{23}	1×10^{-4}
b_{31}	-2.9×10^{-3}
b_{123}	-2.25×10^{-4}

The Fisher test is done for adequacy of model at 5% significance level

$Sy^2 = 3.05*10^{-6}$
$Sad^2 = 0.00$
F-model = Sad^2 / Sy^2
= 0
F-table = 3.8

Since F-model ≤ F-table,

Therefore model is adequate in linear form**.**

When the model is adequate in linear form, then the t-test is conducted to test the significance of each regression coefficient. The t-table value is 2.306. The t values for each regression coefficient is tabulated as follows

Table No 5: t -ratio values for each regression coefficient

Coefficient	t-ratio	Remark
b_0	58.79	Significant
b_1	24.78	Significant
b_2	1.012	Not significant
b_3	14.53	Significant
b_{12}	0.08	Not significant
b_{23}	0.16	Not significant
b_{31}	4.69	Significant
b_{123}	0.36	Not significant

The coefficients b_0, b_1, b_3, b_{123} are significant. Non-significant coefficients are to be eliminated from the model to arrive the final form of mathematical model in linear form as,

$Y= b_0+b_1X_1+b_3X_3+b_{123}X_1X_2X_3$

$Yp(Ra)=2.3318+0.6160X_1-0.0430X_3-0.10754X_1X_2X_3$

Substituting the factors in place of X_1, X_2 and X_3 we get

Y_{Ra}= 5.5951 + (-0.021*Ton) + (-1.032*WT) + (-0.2451*SV) + (8.6*10-3*Ton*WT) + (0.0258*WT*SV) + (2.042*10-3*Ton*SV)+(-2.15*10-4*Ton*WT*SV)

3.11 Analysis of Variance

Analysis of variance is done to find out the percentage contribution of each factor and relative significance of each factor. The ANOVA table for 2,3model is shown in below table.

Table No.6: Percentage Contribution Values

Factor	% Contribution
X_1	71.32
X_2	0.117
X_3	24.29
X_{12}	7.54×10-4
X_{23}	3.01×10-3
X_{31}	2.537
X_{123}	1.52*10-2

3.3 Response surface methodology

Response surface methodology is a collection of experimental strategies, mathematical methods and statistical inference which enable an experimenter to make efficient empirical exploration of the system of interest. It is a collection of mathematical and statistical techniques that are useful for modeling and analysis in applications where a response of interest is influenced by several variables and the objective is to optimize the response. In this in this Experimentation, the outputs obtained are to be incorporated into the historical data of RSM in Design Experts Software and the optimum value of the outputs for the suggested model is obtained.

The design matrix along with the outputs is to be incorporated into the historical data of RSM in Design Experts Software. Next the evaluation is done and the order is selected as per the requirement. The results are evaluated and the required model is suggested. After entering the response

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data in the Design Layout view, a response is chosen by clicking on the corresponding node under Analysis.

$$MRR = 0.036 + 0.015*A - 6.250E\text{-}004*B - 8.975E\text{-}003*C + 5.000E\text{-}005*AB - 2.900E\text{-}003*AC + 1.000E\text{-}004*BC$$

Final Equation in Terms of Actual Factors

$$MRR = -0.19444 + 2.09850E\text{-}003*Ton - 5.70000E\text{-}004*WT + 1.27225E\text{-}003*SV + 2.00000E\text{-}006*Ton*WT - 1.45000E\text{-}005*Ton*SV + 2.00000E\text{-}006*WT*SV$$

3.31 Optimization

In numerical optimization, select the criteria as MRR and goal is to minimize and in the solution the optimum value obtained is 0.0469 and the following graphs are obtained.

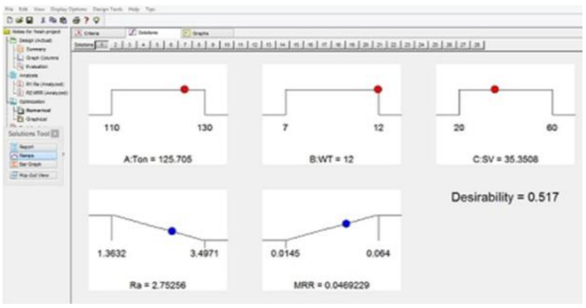

Fig 2: Numerical Optimization of MRR

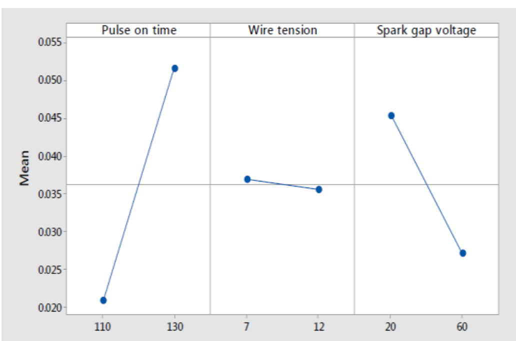

Fig 3: Main effects plot for MRR

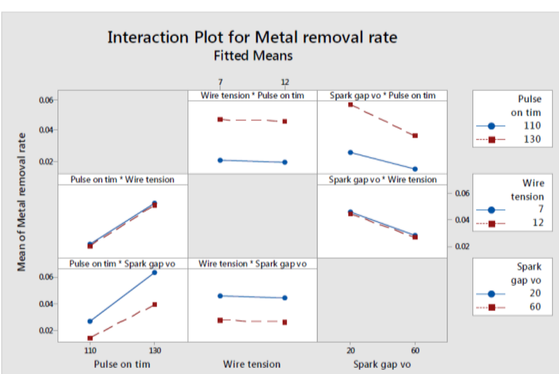

Fig4: Interaction Plot for MRR

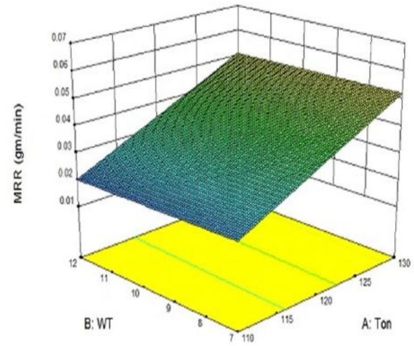

Fig. 5: Analysis of MRR: Model Graph (Ton vs WT)

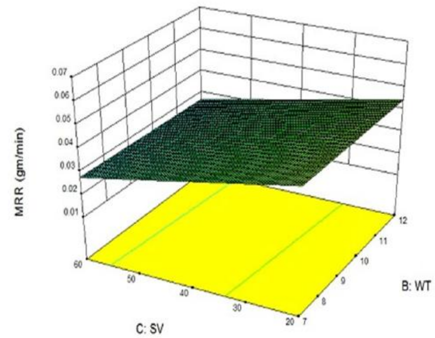

Fig. 6: Analysis of MRR: Model Graph (WT vs SV)

4. Conclusion

From Fig. 3, it is concluded that parameter Wire Tension(X_2) not highly contribute in MRR whereas by increasing the value of Ton, the MRR increases and by increasing the values of SV, the MRR decreases. The most significant factors for metal removal rate are Ton, SV, while interaction of Ton and SV are significant role. Wire tension is very less significant for metal removal rate. The optimum value obtained from RSM methodology for the maximization of MRR is 0.0469.

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