International Journal of Mechanical and Materials Engineering (IJMME), Vol. 7 (2012), No. 3, 203-208.

MATHEMATICAL MODELING OF MATERIAL REMOVAL RATE OF T90Mn2W50Cr45 TOOL STEEL IN WIRE ELECTRICAL DISCHARGE MACHINE

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Received 13 March 2012, Accepted 20 December 2012

ABSTRACT

The present study aims to develop a mathematical model so as to predict material removal rate using response surface methodology in a wire cut electrical discharge machine. In order to establish a mathematical model concerning process parameters and material removal rate, a central composite rotatable design matrix is employed. It includes four variables with five levels. Moreover, the process parameters such as Pulse; on time, off time, peak current, and wire tension are changed accordingly in the process of the experiments. A comparative study is made between the theoretically predicted values of material removal rate and the observations from the experiment. Both the experimental and predicted values are found to be concomitant.

Keywords: Wire electrical discharge machining, Response surface methodology, Central composite design, Analysis of variance.

1. INTRODUCTION

The wire cut electrical discharge machining is administered to machine hard materials that are electrically conductive. It is a burgeoning non-conventional machining process which is known for its high precision. In this process, material removal is achieved by executing a sequence of separate electrical discharges between the wire electrode and the work piece. The dielectric medium determines the discharges, in order that the temperature of the work piece increases only during the time of contact (Lee and Li, 2003). MRR amplifies correspondingly with the peak current when compared with the pulse-on time and pulse-off time. The peak current was the crucial aspect that affects the MRR and surface finish for both finishing and roughing operations (Jaharah et al., 2008). A mathematical model was developed so as to envisage the material removal rate. Scanning Electron Microscope (SEM) is used to analyse the surface integrity and roundness of cylindrical wire electrical discharge turning process. Brass and carbide were used as a work material (Jun et al., 2002a and 2002b). The temperature increases makes the exposed area of the electrical discharges to melt and vaporize. The important response of the method was the material removal rate (Salonitis et al., 2009). The surface roughness and cutting geometry of tungsten carbide was prefigured using Multi variable regression model and back propagate on neural network model(Panda and Bhoi, 2005; Pradhan and Biswas, 2010). Saha et al. (2008) studied the correlation between the criterions like pulse on time, pulse off time, peak current was estimated using second order multi-variable regression model. It was concluded that material removal mechanism is governed by sparks, making it too stochastic. Various sub factors related to wire electrical discharge machine process were considered and machining performance with different materials was evaluated (Saha et al., 2008; Liu et al., 2003; Lee and Li, 2001; Ndaliman et al., 2011). Influence of various process parameters on material removal rate, electrode wear rate and surface roughness were calculated with different materials (Puertas et al., 2004; Kao et al., 2010; Yanda et al., 2010). Higher concentration of SiC powder (above 20g/l) tends to increase the surface roughness. SiC powder concentration, with in the experimental range, is found to slightly reduce MRR and EWR compared to machining without SiC powder. The ANOVA revealed that powder concentration is the most influential parameter on surface roughness, than on MRR and EWR. The quadratic term of the factors also has significant effect (Ali et al., 2011).

The experiment was done on ONA R250 WIRE EDM machine. Moreover, the responses were checked experimentally and by using ANOVA, mathematical expression is found out. The results concluded that only power affects surface roughness and no factor affects roundness. Power, wire speed, voltage, wire tension, time-off, servo, and rotational speed are some factors affecting the surface roughness. Among these, wire speed, power, and servo on roundness are significant agents (Mohammadi et al., 2008). Taguchi method was used to optimize the wire electrical discharge machining process parameters and abrasive hot air jet machining processes (Mahapatra and Patnaik, 2007; Jagannatha et al., 2012). Taguchi's robust design approach was used for wire electrical discharge machine (WEDM). The parameter includes pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity. The responses like material removal rate, surface roughness, and wire wear ratio were consulted for every testing. Heat treated tool steel was used as the work piece. It was found out that increase in pulse on time further than level three enhances the surface roughness and wire wear ratio in consequence of greater discharge energy. Increase in wire tension causes wire breakage (Ramakrishnan and Karunamoorthy, 2006). The white layer depth increases with increasing pulse on time during the initial cut. It also decreases with increasing pulse on time during trim cutting. Break even trim cutting speed is detected to be 3 mm/min (Puri and Bhattacharyya, 2005). In this presentation, process parameters were maximized by response surface methodology so as to predict the material removal rate (Kansal et al., 2005). Variations in material removal rate (MRR), surface roughness (Ra) and corner deviation (CD) were analyzed for wire electrical discharge machine (WEDM) process with pure tungsten as work material. A fusion technique that comprise response surface methodology (RSM) and back-propagation neural network (BPNN) integrated simulated annealing algorithm (SAA) was used. Higher pulse on time caused the high MRR but at same time it produced rough surface (Yang et al., 2012). Already some study has been carried out in developing a mathematical model and to analyze the wire cut electrical discharge machining process to predict the efficiency in terms of material removal rate. In the present study, a mathematical model has been formulated in order to calculate the material removal rate by means of response surface methodology. Analysis of variance is applied to validate the model.

2. RESPONSE SURFACE METHODOLOGY

The response surface methodology (RSM) is a set of mathematical and statistical techniques that are valuable for the modelling and to analyse the problem which is directed by a number of variables and hence the goal is to optimize the response. Response surface methodology also assesses relationship among one or more measured response and the crucial input features. Based on the model, a near optimal point can be construed. It is frequently executed in the characterization and optimization of processes. The mathematical model used is:

$$Y = f\,(\text{pulse on time, pulse off time, peak current and wire tension}) + \varepsilon \qquad (1)$$

Where,

Y = machining response
t_{on} = pulse on time
t_{off} = pulse off time
I_P = peak current
W_T = wire tension
ε = fitting error.

The quadratic equation for a nonlinear relationship between a specific response and four independent process parameters can be given as

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_1X_2 + b_6X_1X_3 + b_7X_1X_4 + b_8X_2X_3 + b_9X_2X_4 + b_{10}X_3X_4 + b_{11}X_1^2 + b_{12}X_2^2 + b_{13}X_3^2 + b_{14}X_4^2 + \varepsilon \qquad (2)$$

The afore-mentioned equation is applied to explain the functional relationship among the machining response. Y X_1, X_2, X_3, and X_4, coded values of input process parameters pulse on time, pulse off time, peak current, and wire tension, respectively. The coefficient, b_0, b_1, b_2, b_3, and b_4 etc. are to be estimated by the method of least squares. The calculated coefficients of the equation (2) need to be tested for statistical significance.

3. EXPERIMENTAL DETAILS

With the intention of developing a model based on experimental data, meticulous examination of the experiment is indispensable. Pulse on time, pulse off time, peak current, and wire tension were the parameters acknowledged for experimentation and analysis of wire cut electrical discharge machining of T90Mn2W50Cr45 tool steel.

3.1 Experimental design matrix

Properly prepared design matrix can considerably decrease the number of experiments. Hence, it is necessary to develop a good design matrix to conduct the procedures. Table 1 illustrates the range of values of each factor that are chosen based on pilot experimentation set at five diverse levels

Table 1 Process parameters and their Limits.

Coded value	Parameters	Factors Level				
		-2	-1	0	1	2
X_1	t_{on}	105	110	115	120	125
X_2	t_{off}	43	48	53	58	63
X_3	I_P	150	170	190	210	230
X_4	W_T	4	6	8	10	12

t_{on} - Pulse on time(μs); t_{off} - Pulse off time(μs),
I_P - Peak Current (A); W_T - Wire Tension (g)

The selected design matrix is a central composite rotatable, four factor and five level factorial design comprising 31 set of coded conditions and composing a complete duplication of 2^4 (= 16) full factorial design for self-determining features each at five levels with 16 cube points in addition to eight star points and seven replicated at centre points. All the wire cut electrical discharge machining process attributes at the intermediate (0) level constitute the centre points while the blend of each process parameters at either its lowest value or its highest value ± 2 with the other parameters of the intermediate levels form the star points. Therefore, the 31 experiments authorized the evaluation of the linear, quadratic and two way interaction outcomes of the wire cut electrical discharge machining variables on the material removal rate (Cochran and Cox, 1965). The subsequent transforming equation is used to get the coded values of variables used in Eq. (2)

$$X_i = \frac{\text{Chosen parametric value - Central rank value}}{\text{Incrementral paramertic value}} \qquad (3)$$

Where X_1 is coded value of pulse on time (t_{on}), X_2 is the coded value of pulse off time (t_{off}), X_3 is the coded value of peak current (I_P), and X_4 is the coded value of wire tension (W_T).

3.2 Experimental set up

An “ELETRA SPRINTCUT 734” wire-cut EDM machine, with a pulse generator, was used for conducting the experiments. The electrolytic copper wire of diameter 0.25 mm acted as an electrode. For every experiment, deionised water served the purpose of dielectric fluid.

The T90Mn2W50Cr45 tool steel material (American designation is ASTM O2) of diameter 12 mm and 15 mm length was used as working material in this study. Table 2 illustrates the chemical composition of the work material. The properties of working material are given in Table 3. Photographic view and schematic illustration of experimental set up is given in Figure 1 and Figure 2, respectively.

Table 2 Chemical composition of test specimen (wt %).

C	Mn	Si	S	P	Cr	V	W
0.9	1.5	0.3	0.02	0.02	0.5	0.2	0.5

Table 3 Properties of T90Mn2W50Cr45 tool steel.

Melting point (^oC)	1370-1400
Density (kg/m^3)	8000
Thermal conductivity (W/m.K)	16-16
Electrical resistivity (Ω.mm^2/m)	0.7
Thermal expansion coefficient	16-17 x 10^{-6}/K
Ultimate tensile strength (MPa)	1158
Hardness (HB)	335

Figure 1 T90Mn2W50Cr45 tool steel material mounted on WEDM.

3.3 Experimental procedure

The T90Mn2W50Cr45 tool steel material of 15 mm length and 12mm diameter size for each specimen is mounted on the ELETRA SPRINTCUT 734" wire-cut EDM machine. The experiments were conducted in 31 runs for diverse mixture of process aspects as given in Table 4.

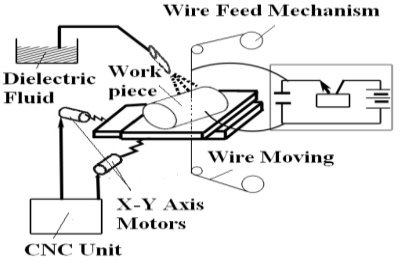

Figure 2 Schematic diagram of WEDM process.

After machining, the material removal rate was measured. The following formula is used for calculating the material removal rate:

$$MRR = \frac{W_i - W_f}{t} \quad (4)$$

Where W_f was the final machining weights of work piece material and W_i was the initial machining weight of the work piece material, respectively. 't' refers to the machining time. The weight of the work piece materials are measured by an electronic weighing machine.

4. RESULTS AND DISCUSSION

The pulse on time, pulse off time, peak current and wire tension were independent variables considered for the prediction of Y response. Based on the independent process parameters, their levels were calculated. The range of values of process parameters for each of the experiments are given in Table 4. The predictable coefficients obtained are employed to generate the model for the response consideration. The full form of the desired mathematical model is given as:

$$MRR = - 8.6 + 0.040 X_1 + 0.034 X_2 + 0.0622 X_3 - 0.468 X_4 + 0.000290 X_1{}^{*}X_1 + 0.000455 X_2{}^{*}X_2 - 0.000028 X_3{}^{*}X_3 + 0.00847 X_4{}^{*}X_4 - 0.000075 X_1*X_2 - 0.000338 X_1*X_3 - 0.00048 X_1*X_4 - 0.000473 X_2*X_3 + 0.00150 X_2*X_4 + 0.00150 X_3*X_4 \quad (5)$$

4.1 Scrutinizing the adequacy of the model expounded

The adequacy of the model is checked by means of the analysis of variance (ANOVA) technique. In this way, if the calculated *F*-ratio of the developed model did not exceed the standard tabulated values of *F*-ratio for desired level of confidence (92% for material removal rate) the model is deemed to be within the confidence level. Table 5 elucidates the ANOVA table for material removal rate. Some of the P-values for different set of analysis in Table 5 are less than 0.05 (given as superscript *). Those sets of analyses are significant. Also, the mean effect of linear factor pulse on time (X_1) is significant. The model contain a square effect of wire tension (X_4) are significant. The P-value of wire tension 0.023 is below 0.05 for material removal rate. In addition the model contains a single, two way major interaction (pulse off time x peak current) and (peak current x wire tension). The P-values of 0.018 and 0.004 for pulse off time x peak current, and peak current x wire tension respectively are less than 0.05 for response. From the above analysis it is understood that peak current (X_3) as a linear factor is not significant. When combined with pulse off time (X_2) and with the wire tension (X_4), the analyses become significant. The interaction of parameters (X_3 and X_4) is relatively essential for material removal rate. Other model terms may be considered insignificant for material removal rate prediction. These insignificant model terms can be eliminated and it may emanate as an enhanced model. The Eq. (5) is reduced to Eq. (6), which is the final empirical model for material removal rate.

$$MRR = - 8.6 + 0.040 X_1 - 0.468 X_4 + 0.00847 X_4{}^{*}X_4 - 0.000473 X_2*X_3 + 0.00150 X_3*X_4 \quad (6)$$

Further, using this model, the experimental and predicted values were plotted in a scatter diagram (Figure 3). The observed values and predicted values of the response were scattered close to the 45^0 line, indicating an almost ideal match of the developed model. These figures and ANOVA analysis for material removal rate indicates that the model is extremely convincing and sufficient to embody the actual correlation between the process parameters and response, with very small P value (<0.05) and high values of coefficient of determination (R^2 = 0.92).

Table 4 Design matrix and response.

Expt. No.	t_{on}	t_{off}	I_P	W_T	MRR	
					Observed	Predicted
1	120	48	210	6	0.644	0.608
2	110	58	210	10	0.220	0.224
3	110	58	170	10	0.187	0.194
4	120	58	210	6	0.488	0.433
5	110	58	210	6	0.184	0.198
6	120	58	170	6	0.737	0.778
7	110	48	210	6	0.336	0.316
8	120	58	170	10	0.618	0.545
9	120	48	170	10	0.474	0.471
10	120	48	210	10	0.686	0.655
11	110	58	170	6	0.518	0.458
12	110	48	210	10	0.351	0.332
13	110	48	170	6	0.315	0.337
14	120	48	170	6	0.811	0.714
15	110	48	170	10	0.096	0.063
16	120	58	210	10	0.490	0.490
17	105	53	190	8	0.079	0.067
18	115	43	190	8	0.385	0.461
19	115	53	150	8	0.348	0.386
20	115	53	190	4	0.584	0.637
21	115	53	190	12	0.405	0.420
22	115	53	230	8	0.279	0.310
23	115	63	190	8	0.424	0.417
24	125	53	190	8	0.682	0.711
25	115	53	190	8	0.352	0.379
26	115	53	190	8	0.311	0.379
27	115	53	190	8	0.330	0.379
28	115	53	190	8	0.345	0.379
29	115	53	190	8	0.356	0.379
30	115	53	190	8	0.360	0.379
31	115	53	190	8	0.368	0.379

4.2 Testing the coefficients for significance

From the ANOVA Table 5, material removal rate of the regression co-efficient R was 0.959. Calculated value was statistically significant and it was significant at 95% confident level. The values of the regression coefficient give a suggestion to what degree the factors change the response. Unimportant co-efficient can be discarded without renouncing much of the precision to evade unwieldy mathematical effort. For achieving this purpose, t-test and *F*-tests were used. The statistical software was used to perform the test of significance. For the period of backward steps, a variable was eliminated from the model and for the period of forward steps; a variable is added to the model. Subsequently, to determine the significant coefficient, these coefficients were used to construct the critical models.

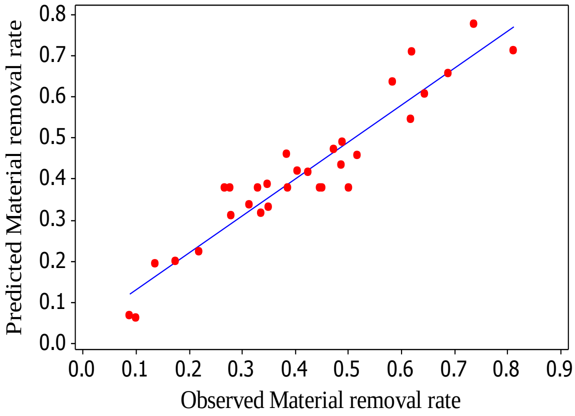

Figure 3 Predicted and observed value of material removal rate.

4.3 Effect of working parameters on the material removal rate

Figure 4 demonstrates the variation of material removal rate for the four variables pulse on time, pulse off time, peak current and wire tension on material removal rate From Figure 4, it was understood that, pulse on time (105-125 µs) is directly proportional to the material removal rate whereas Wire tension (4-12 g) is inversely proportional to the material removal rate.

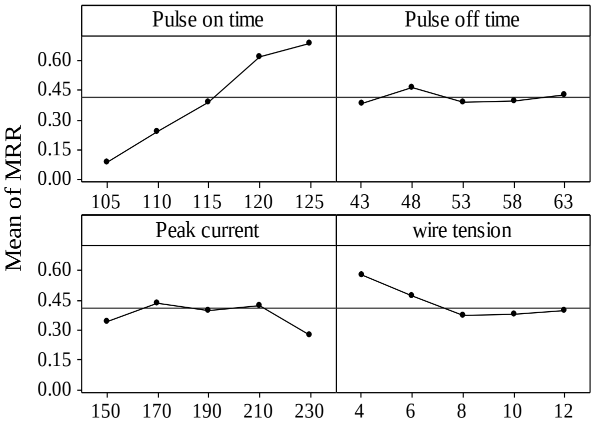

Figure 4 Main effects plot for material removal rate.

For the variation of Pulse off time (43-63 µs) and peak current (150-230 A), the material removal rate is more or less constant. Figure 5 shows the pictorial representation of effect of pulse on time (105-125 µs) and wire tension (4-12 g) on the material removal rate, when peak current (150-230 A) and pulse off time (43-63 µs) remain constant. From Figure 5 shows that the material removal rate is low for the lower value of pulse on time and optimized value (9g) of the wire tension. Material removal rate is incredibly high for the lower wire tension and higher pulse on time.

Table 5 ANOVA table for material removal rate.

Source	DF	SS	MS	F	P
Model	9	0.9532	0.0680	13.14	0.000*
X_1	1	0.7336	0.7336	141.62	0.000*
X_2	1	0.0088	0.0088	1.71	0.209
X_3	1	0.0027	0.0027	0.52	0.478
X_4	1	0.0504	0.0504	9.73	0.007*
X_1^2	1	0.0005	0.0005	0.10	0.598
X_2^2	1	0.0024	0.0024	0.47	0.411
X_3^2	1	0.0064	0.0064	1.25	0.410
X_4^2	1	0.0328	0.0328	6.33	0.023*
X_1*X_2	1	0.000056	0.000056	0.01	0.918
X_1*X_3	1	0.0182	0.0182	3.51	0.079
X_1*X_4	1	0.0003	0.0003	0.06	0.795
X_2*X_3	1	0.0357	0.0357	6.89	0.018*
X_2*X_4	1	0.0036	0.0036	0.69	0.417
X_3*X_4	1	0.0573	0.0573	11.07	0.004*
Residual Error	16	0.08289	0.005180		
Lack-of-Fit	10	0.03350	0.003350	0.41	0.900
Pure Error	6	0.04938	0.008230		
Total	30	1.03616			
R^2= 0.92					

*Significant

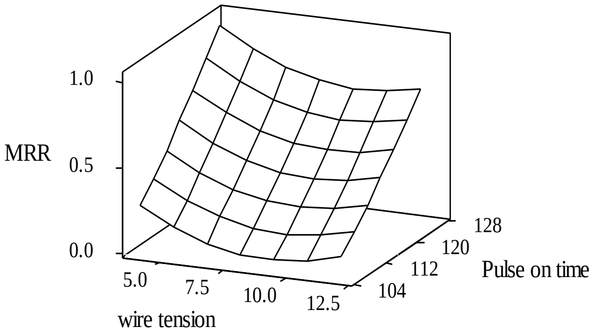

Figure 5 Surface plot of material removal rate vs. pulse on time, wire tension.

Figure 6 establishes the material removal rate for the variation of peak current and pulse on time. It also shows that the material removal rate was low for the optimized value of pulse on time and for the variation of peak current. The material removal rate was high for the maximum pulse on time and for the minimum peak current. According to Figure 7, material removal rate is optimum for the optimum values of peak current (200 A) and wire tension of (7.5 g).

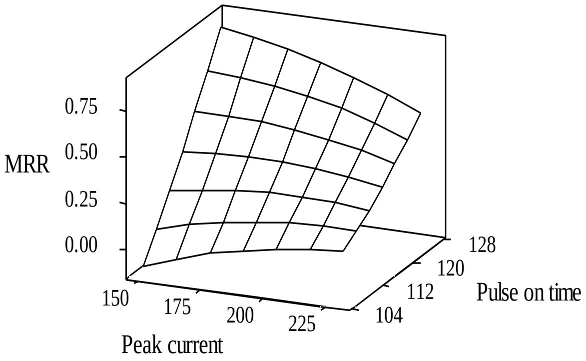

Figure 6 Surface plot of material removal rate vs. Pulse on time, Peak current.

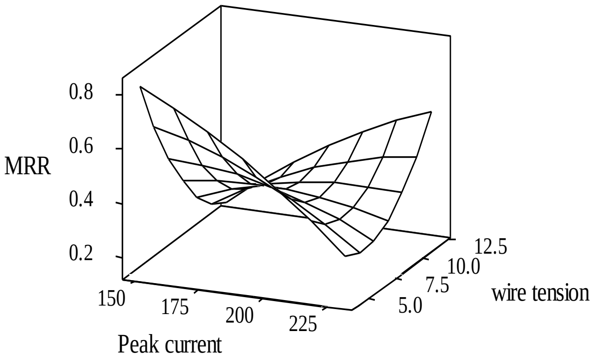

Figure 7 Surface plot of material removal rate vs. wire tension, peak current.

5. CONCLUSION

The experimental investigation asserts the machining criteria like material removal rate which is influenced by a range of major machining parameters considered in the current research. Response surface methodology adopted in this research has ascertained its adequacy as an efficient means for analysing the machining process. From the study, the subsequent deductions were drawn

- Peak current and wire tension of the regression models were observed to be greatly important when equated with other parameters. The intended model for material removal rate was considered to be sufficient and can be adopted to envisage the different facets contained by the investigational range.
- In this research paper, wire electrical discharge machining process parameters were optimized by the use of response surface methodology. The material removal rate was investigated experimentally for the variation of pulse on time, pulse off time, peak current and wire tension.
- Pulse on time is directly proportional to the material removal rate whereas Wire tension is inversely proportional to the material removal rate.

- Material removal rate is very high for the lower wire tension and higher pulse on time.
- Material removal rate was optimized at 0.5 for the optimum value of peak current (200 A) and wire tension of (7.5g).
- For the wire tension less than 7.5g material removal rate was high and when more than 7.5g material removal rate remains constant.

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