Modeling and Analysis of MRR in WEDMed WC-CO Composite by Response Surface Methodology

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Abstract

Wire electro discharge machining (WEDM) was applied to machine tungsten carbide–cobalt (WC-CO) metal matrix composite. It finds increasing application in auto, aeronautical and oil drill application. The material is extremely hard, brittle and tool grade. The present work is undertaken on 10% cobalt, 90% tungsten grade in which keen study is lacking. Amongst many variables, On-time, Off-time and ignition current were shortlisted as critical input parameters. The goal is to identify the input parameter level that maximizes the material removal rate. The input parameters for the experiments were selected after considering previous related work, manufacturer's catalog and industrial expert's opinion. From Taguchi L27 experimental plan, the Box-Behnken trials for 14 experiments were derived in order to model and to predict the output response with good accuracy. The investigation was carried out on the high speed Sodick machine so that it aligns with industry requirement of higher productivity. Response surface modeling and regression analysis was done. Analysis of variance was used to isolate parameters that are critical from pooled data. The experimental results were verified by running at recommended setting of the findings. The outcome was encouraging. Output response improves with on-time at 8 μ- Sec, off -time 15 μ- Sec and ignition current of 16 amperes. It was found that overall metal removal rates increased by 13%, to 17.42 mm3/min from the process average rate of 15.15 mm3/min. A mathematical equation was derived to predict performance. Surface, response contour plots were utilized to analyze performance. The validity of derived model was verified. Since error obtained was 4.5%, higher coefficient of determination is 87% and adequate precision was >4, the model is valid.

Keywords: WEDM, material removal rate, WC-CO, response surface, regression analysis

1. Introduction

WEDM is a versatile thermo-electric process. The electrical circuit produces controlled tiny sparks between the wire electrode and work. These sparks create high temperature which melts and vaporizes the work material. The control parameters are spark exposure time (On-time), capacitor charging time (Off-time), current intensity (Ignition- current), electrode wire tension, dielectric supply pressure, work material melting temperature, wire feed speed, machine rigidity-capability, which can classify as machine parameter, material parameter, electrical parameter, and mechanical parameter. Three important parameters of significance were selected in the present work. Better productivity and economy is attained when the interactions among variables are understood. Many works were undertaken for WEDM optimization process variation in parameter makes generalization difficult. Response-surface methodology (RSM) is one of the important techniques in statistics used to determine the relationship between the effects of process parameters on the coupled responses [1, 2]. A lot of work being done with other materials but with WC-CO composite works undertaken pre were few. Kanagarajan and Palanikumar [3], have used the RSM model to maximize MRR on WC-30%Co composites. In the present study, WC-CO with cobalt binder (10%) was machined by WEDM.

Literature review states RSM is a combination of mathematical and statistical techniques and is used for developing improved and optimizing the parameter [4] for the output response of material removal rate and surface roughness. Hamdi Aouici analyzed surface roughness and cutting force components in hard turning with CBN tool and predicted model for cutting conditions optimization using RSM. Pragya shandilya and Jain [5] varied four WEDM parameters servo voltage, pulse-On-time, pulse-Off-time and wire feed rate on SiCp/6061 aluminum MMC with surface roughness as a response parameter. Choudhury and El-Baradie [6] have used response surface methodology for predicting surface roughness of high strength steel. Samish Habib [7] developed mathematical models by the RSM for EDM. Recently, Rajamumurugan and Palaikumar. K [8] analyzed glass fiber reinforced polymer by response surface methodology. Muthuraman and Ramakrishnan. R [9] studied Micro structural Characterization of Wire Electro Discharge Machined Tungsten Carbide Cobalt Metal Matrix Composite and concluded On-time and Ignition- current are significant parameters for material removal rate and Off-time is critical to control surface roughness. The same authors applied desirability approach [10] for optimization of WC-CO composite and have observed On-time, Off-time and Ignition- current are critical inputs. Modeling by RSM, could optimize the response parameter better with fewer runs and the 3-D plots provide a better insight in analyzing.

2. Materials and Methods

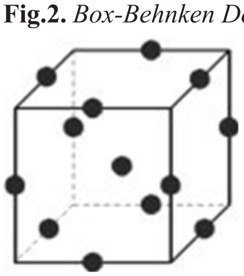
In the present work WC-CO metal matrix composite with 10% cobalt percentage was sliced to size of 15x12.5x10 mm cube by Sodick AQ427 WEDM machine. Copper-zinc wire of 0.20 mm diameter was used as electrodes. The wires were supplied and spent wires were taken away by traction rollers made of ceramic material to reduce wire damage, friction and to enable high speed machining. Used wires were collected in a separate tank . Distilled water was utilized as di-electric fluid to remove debris in order to keep the cutting zone clear and the work surface from heating up. An electrode gap up to 0.5 mm has been kept between wire and work. Dielectric after flushing and filtering will be recycled. The Experiments were planned on Box- Behnken design, 3 parameters, 3 levels, 15 experimental runs.. The experimental plan, levels selected and their range is given in Table 1.

Table 1. *Input parameter levels selected and their range*

Input Parameters	Low (-1)	Medium (0)	High (+1)
A-On-time (µ- Sec)	6	8	10
B-Off-time (µ- Sec)	15	20	25
C-Ignition- current (A)	8	12	16

Fig.1. *Photograph shows the schematic diagram and the setup of WEDM process .*

Fig.2. *Box-Behnken Design -3 Factors*



The material removal rate was estimated using Eq.1.

Material Removal Rate (MRR) = (V_c/T) mm3/min (1)

Where, V_c is the volume of the machined cuboids' on the work-piece and T is the time taken in minutes.

The calculated material removal rate is presented in table 3.

2.1 Response surface methodology

Response surface methodology can identify the influences of input parameters and output [8]. The design procedure of RSM is given below [9, 10].

i) Designing a series of experiments of adequate and reliable measurements of the response of interest.

ii) Developing a mathematical model of the response surface with the best of fit.

iii) Determining an optimal set of experimental parameters that results in maximum or minimum value of the response.

iv) Plotting the interaction effects of the parameters through 2D contour plots and three dimensional plots.

The Box-Behnken response surface design is an independent quadratic design that does not contain embedded factorials [11]. The treatment points are at the midpoint of the edges of the process space and at the center of the cube as shown in Fig.2. The design is nearly rotatable with 3 levels for each factor. Table 2 shows the detailed design.

Table 2. *Box-Behnken Design*

Factors	Base runs	Base blocks	Replicates	Total runs	Total blocks	Center points
3	15	1	1	15	1	3

The condition with real values, coded values of parameters and experimental results are presented in Table 3.

Table 3. *Box-Behnken design with coded and actual values, predicted and experimental results.*

Test	Coded values			Actual values			Response-MRR		Error
	A	B	C	On-time µ-Sec	Off-time µ-Sec	I.g A	Experiment mm3/min.	Predicted mm3/min	
1	-1	-1	0	6	15	12	11.939	12.070	0.131
2	+1	-1	0	10	15	12	15.983	16.055	0.072
3	-1	+1	0	6	25	12	16.938	16.865	-0.073
4	+1	+1	0	10	25	12	13.732	13.79	0.058
5	-1	0	-1	6	20	8	12.813	12.682	-0.131
6	+1	0	-1	10	20	8	8.9904	8.9904	0.000
7	-1	0	+1	6	20	16	17.14	17.237	0.097
8	+1	0	+1	10	20	16	11.266	11.290	0.024
9	0	-1	-1	8	15	8	15.761	15.703	-0.058
10	0	+1	-1	8	25	8	14.842	14.808	-0.034
11	0	-1	+1	8	15	16	19.382	19.416	0.034
12	0	+1	+1	8	25	16	16.154	16.057	-0.097
13	0	0	0	8	20	12	17.420	17.420	0.000
14	0	0	0	8	20	12	17.420	17.420	0.000
15	0	0	0	8	20	12	17.420	17.420	0.000

Regression analysis was done with coded units using Minitab software. The mathematical modelling equation and other parameters obtained are given below.

The regression equation to predict the material removal rate is ,

$$MRR = 17, 42 + 1.0004 A - 0.5255 B + 0.5059 C - 0.9171 A*A + 0.1346 B*B + 0.4484 C*C - 1.8020 A*B + 2.9117 A*C - 0.8910 B*C \quad (2)$$

Where, A-On-Time; B-Off-time; C-Ignition- Current.

S = 2.17950, PRESS = 380.017, R-Sq = 85.13% , R-Sq (pred) = 89.63%, R-Sq (adj) = 84.37% Mean=15. 14669, Adequate precision > 4.

Equation 2 states On-time and Ignition- current tension has a positive influence on the material removal rate. Rise in On-time and Ignition- current augurs well for MRR. In general with On-time, the Ignition- current create sparks, the longer the duration of it, the higher the MRR should be. Off-time has a negative influence on MRR.i.e Higher the Off-time, lower the material removal rate and vice versa. Higher Off-time helps to charge the capacitor, but too much dwell there results in the lesser availability of the machine to remove material .Hence MRR drops. The interaction effect of Off-time also shows negative significance. Among the various models considered in the analysis, the full quadratic model provides a high coefficient of determination (85%) and hence is selected appropriately. The PRESS values for average material removal rate and mean MRR indicates that the full quadratic model is the best fit model for the prediction of material removal rate response

2.2 Analysis of variance

The analysis of variance (ANOVA) was performed to study the effect of the input parameters on the material removal rate and the significance of the individual from the group. For clarity ANOVA was done in both the cases i) without considering the interaction (Table 4) and ii) Considering the interaction (Table 6). Table 4 indicates , Statistically, On-time is the most significant parameter, with low P and high fisher test value F, followed by Ignition current and Off-time.

Table 4. *Analysis of Variance for MRR*

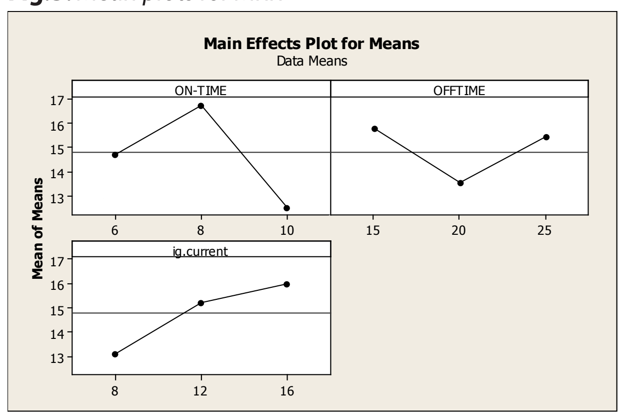
Source	df	SS	**MS**	**F**	**P**
On-Time	2	50.81	25.96	5.82	0.028
Off-time	2	2.17	0.80	0.18	0.839
Ig. Current	2	24.84	12.42	2.78	0.129
Error	8	35.69	4.46		
Total	14	113.51			

Table 5. *Response for Signal to Noise Ratios*

Level	On-Time-A	Off-time-B	Ig. Current-C
1	23.24	**23.83**	22.15
2	**24.42**	22.35	23.55
3	21.73	23.73	**23.91**
Delta	2.69	1.48	1.75
Rank	1	3	2

In general, higher the signal to noise ratio the better the output response will be. Table 5 presents the calculated signal to noise ratio (S/N). Delta is the difference between highest and lowest S/N for a particular input parameter. It is observed, On-time holds the highest rank and hence most significant, followed by ignition current .Any change in the values of these parameters will affect MRR sharply. With lower rank Off-time is least significant. What ever modification, optimization can be done with this parameter. Corresponding to the levels from the graph of fig.3 the following optimization sequence levels can be deduced.A2B1C3 provides maximum S/N and hence is an optimum solution.i.e. The MRR is maximum when On-Time is 8 μ -Sec, Off-time at15 μ -Sec and Ignition- current of 16 A.

Fig.3. *Mean plots for MRR*



From Fig.3 it is evident, i) when the On-time is low, MRR is low. With medium On-time MRR is high. Further rise in

On-time, results in lower MRR as shown in decline in the graph. ii) For Low Off-time MRR is highest. Medium Off-time yields lowest MRR. High Off-time produces moderate MRR. III) Ignition current, when it is low, the response tends to be low. Higher current values increase the MRR.

Table 6 shows ANOVA result considering interaction. Since the model considered involves not only individual parameters but also their interaction among themselves.

Table 6. *Analysis of Variance for MRR*

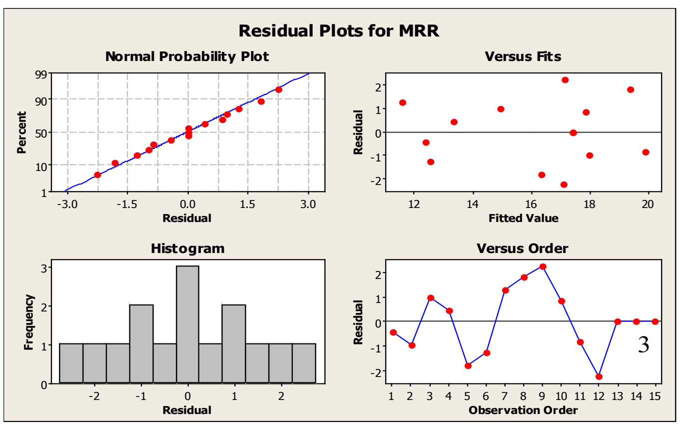
Source	df	SS	MS	F
Model Regression	9	95.802	10.6447	2.24
Linear	3	12.262	4.0875	0.86
A	1	8.006	8.0060	1.69
B	1	2.209	2.2092	0.47
C	1	2.047	2.0473	0.43
Square	3	33.462	11.1541	2.35
A*A	1	32.683	31.4201	6.61
B*B	1	0.037	0.0669	0.01

C*C	1	0.742	0.7423	0.16
Interaction	3	50.077	16.6925	3.51
A*B	1	12.989	12.9888	2.73
A*C	1	33.913	33.9132	7.14
B*C	1	3.176	3.1755	0.67
Residual Error	5	23.751	4.7502	*
Lack-of-Fit	3	23.751	7.9170	
Pure Error	2	0.000	0.0000	
Total	14	119.553		

The model having a chance of probability of P > F is less than 0.05. The obtained F value was 2.24. Hence the model terms have only 0.194% chance of this to occur due to noise. The adequacy of models had been analyzed by residuals [12].

The probability plot Vs residuals are given in Fig. 3. It also presents residuals against predicted response.

Fig.4. *Normal probability plot, residuals Vs. fits and residuals Vs. experimental run*



In Fig.4, the normal probability plot, since the points closely form an approximate straight line, it implies data follow approximately normal distribution. The odd points, since not deviating much from the straight line, are less in significance to affect the model. Hence the normal distribution provides an excellent model for the data. It shows a good correlation between measured and predicted values of the model. Rsq of 85%and adjusted Rsq of residuals per unit degrees of freedom is 84.37% confirms the model is reliable with a probability of significance of 95%. The Residuals Vs Fit graph shows a pattern of randomness in scatter which indicates un-biased variance. In the time series plot of Residuals Vs. Experimental run shows uniformity in variation.

The influence of input variables interacting within themselves and also with output response, corresponding to Table 6 are shown with the help of surface plots and contour plots in Fig. 5, and Fig.6 respectively. RSM quantifies the relationship between the controllable input parameters and the obtained response [12, 13]. The surface plot represents MRR values at various zones. The dark green area indicates the highest MRR zone, Blue indicates the lowest. The target point is at 17.420 mm3/min at the center.

Fig.5. *Surface plot of MRR*

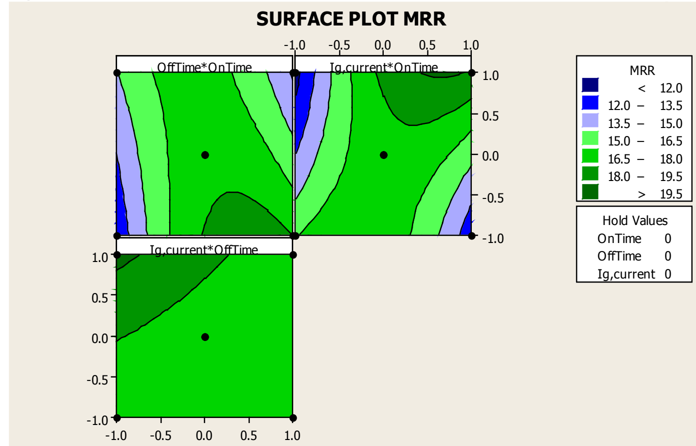
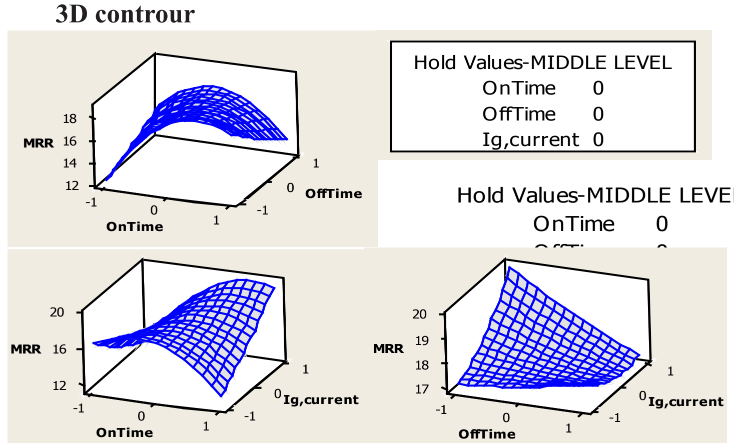


Fig.6 show the 3-D contour plot with MRR on Y-Axis, keeping one parameter in turn constant and varying the other two with respect to MRR. It is seen, when Ignition- current is held constant at mid value (12A). Here, with low On-time (6 μ- Sec), rise in Off-time (20 μ- Sec), the MRR increases to peak, then it falls off. With higher Off-time (25 μ- Sec) MRR increases in maximum value then falls off again. Low On-time indicates low sparking, hence less MRR. At 8 μ- Sec of On-time the performance peaks. A further rise in On-Time (10 μ- Sec) reverts back to low MRR due to the fact that the spark gets diluted, less intense spark cannot retain high MRR effectively. With On-time held constant at (8 μ- Sec), higher Ignition- current increased the MRR drastically, even at low Off-time (15 μ- Sec). With high Off-time (25 μ- Sec), high Ignition- current the MRR drops due to lesser sparking frequency.

Fig.6. *Contour plot of MRR*

3D controur



From the 3D plot it is evident that, input parameter individually as within themselves interact. The output response MRR, is influenced as observed below.

1. On-time is high, MRR is low. On-time at medium level, MRR is higher. On-time low, MRR is moderate.

2. Ignition- current is high, MRR is also high. When current is low, MRR also lowered.

3. With Ignition- current held constant, maximum MRR occurs in medium On-time and medium Off-time.

4. Off-time kept as constant, low On-time and high Ignition-

current could produce high MRR.

5. With On-time held as constant, low Off-time as well as high current results in high MRR.

3. Results

It is generally held, that the higher the Off-time, the higher the capacitor charging time, and higher ignition current means higher MRR .Through this work (experiment 11&13 it was demonstrated MRR (19.382 &16.152 mm3/min) can be maximized by setting at medium On-time((8 µ- Sec).This result is significant as with low intensity current, lesser Off-time, and medium On-time ,maximum overall MRR could be attained.This may be due to more time available to spark for machining.It was also observed from Fig.6 very low Off-time reduces output response.This could be due to Smaller charging time resulting in weaker sparks, not strong enough to melt, vaporize cobalt binder.It is recommended that keeping the Off-time at 15 µ - Sec,the On-time at 8µ- Sec and Ignition- current at 16 A the output response MRR can be maximized.

4. Confirmation test

To confirm whether the model is effective and adequate, confirmation test was carried out. For those within the levels previously defined was selected. The predicted and experimental value error percentage was estimated. The result is presented in Table 7.

Table 7. *Confirmation test Result (Experimental Vs RSM model)*

Test Input Parameters		RSM output Responses	
On-time (µ- Sec)	8	Experimental (mm3/min)	17.42
Off-time (µ- Sec)	15	RSM predicted (mm3/min)	17.465
Ignition- current (A)	16	Error (%)	4.5

Since the error involved in the predicted result of the model and actual experimental result obtained during the confirmation test is 4.5% the developed model can be useful in predicting output MRR within an error of 4.5%, for any parameter combination within the limits of range taken in the analysis.

5. Conclusion

The full quadratic factor for analysis provides the best fit. The model was verified for fitness, prediction and experimentation. This model can be useful for academic and manufacturing community to estimate obtainable MRR within an error of 4.5% without actually machining it Response surface, the regression analysis model can adequately provide required information about WEDM output.

6. References

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