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Parametric Optimization during wire Electrical Discharge Machining using Response Surface Methodology

Pardeep Kumar

Poornima University, Ramchandrapura, Sitapura Extension, Jaipur-303905
E-mail: pkdeepak4@gmail.com

Abstract—*Present study has been made to optimize the process parameters during machining of WC-24%Co Composite by wire electrical discharge machining (WEDM) using response surface methodology (RSM). Four input process parameters of WEDM (namely servo voltage (V), pulse-on time (TON), pulse-off time (TOFF) and Current (A) were chosen as variables to study the process performance in terms of cutting speed (CS) and wire wear rate (WWR). The analysis of variance (ANOVA) was carried out to study the effect of process parameters on process performance. In addition mathematical models have also been developed for response parameter. Therefore, using desirability function, parameters have been predicted for maximizing the machining speed and minimization of wire wear rate.*

1. INTRODUCTION

Cemented tungsten carbides (WC) are commercially one of the oldest and most successful powder metallurgy products, formed by sintering of WC powder with the binder (typically Co or Ni) at temperature near the melting point of the metal. Matrices of ductile metals, such as cobalt, greatly improve its toughness so that brittle fracture can be avoided. WC is extreme hard and corrosion resistance material which has raised its demand in the production of cutting tools, dies and other special tools and components. Tungsten carbide composite (WC-Co) is a difficulty to machine material since it possesses excellent mechanical properties like high strength, high hardness and high melting temperature. Therefore, efficient machining of tungsten carbide is an inevitable challenge for manufacturers. Several attempts have been made on machining of tungsten carbide using conventional process like turning, milling and grinding. However, the cost associated with these processes is very high since the material removal rate is very low as well as machining of complex profiles is difficult. Wire electrical discharge machining (WEDM) is a non conventional machining process which overcomes the difficulties in machining of tungsten carbide composite. WEDM is a thermo electrical process in which material is eroded from the workpiece by a series of discrete sparks between the workpiece and the wire electrode (tool) separated by a thin film of dielectric fluid (deionized water) that is continuously fed to the machining zone to flush away the eroded particles. The movement of wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the workpiece. The schematic diagram of WEDM is shown in Fig. 1. along with dielectric flow, power supply, working table and other control devices. It is evident from Fig. 1. that it is absolutely essential to hold the wire in a designed position against the object because the wire repeats complex oscillations due to electro-discharge between the wire and workpiece. Normally, the wire is held by a pin guide at the upper and lower parts of the workpiece. In most cases, the wire will be discarded once used. However, there are problematic points that should be fully considered in order to enhance working accuracy.

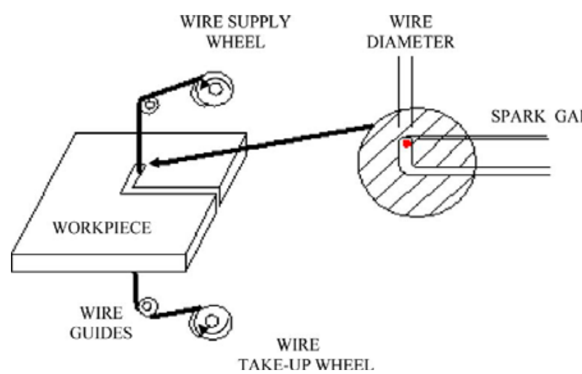

Fig. 1: Representation of WEDM process

Several attempts have been made to determine optimal machining conditions for WC-Co composite on EDM and WEDM. Lee and Li 2001; investigated the effect of electrode materials, electrode polarity, open circuit voltage, peak current, pulse duration, pulse interval and flushing on the machining characteristics, such as, material removal rate (MRR), surface finish and relative tool wear in machining of tungsten carbide with die sinking EDM. It was found that the surface roughness is a function of two main parameters, peak current and pulse duration. At high peak current and/or long pulse duration rough surface and abundance of micro-cracks was observed. Mahdavinejad and Mahdavinejad (2005) studied the instability in EDM of WC-Co composites. This machining instability was mainly due to open circuit, short circuit and arcing pulses. Increase in pulse duration results in more melting and recasting of material, which causes arcing and rougher surface. Assarzadeh and Ghoreishi (2013); investigated the effect of input parameters like discharge current, pulse-on time, duty cycle, and gap voltage on the material removal rate, tool wear rate, and average surface roughness while machining of WC-6%Co composite with WEDM. They concluded that the MRR increases by selecting both higher discharge current and duty cycle which means providing greater amounts of discharge energy inside gap region.

2. EXPERIMENTAL PROCEDURE

2.1. Work material and machining parameters

Experiments were performed on 5-axis sprint cut (epulse-40) WEDM, most widely used in Indian industries, manufactured by Electronica Machine Tools Ltd., India. A diffused brass wire of 0.25 mm diameter was used as the cutting tool. Tungsten carbide composite with cobalt concentration (24%) has been taken as a work material in the form of a rectangular block of thickness of 20 mm. The deionized water was used as dielectric and its temperature was kept at 20^{o}c. In present investigation, four important WEDM parameters, namely pulse-on time (T_{on}), pulse-off-Time (T_{off}), servo voltage (SV) and current have been considered with two levels (Table 1), to study their effect on cutting speed and wire wear rate as response parameter. In present machine tool, range of the important parameters is as follows: discharge current, 10–230 amp; pulse-on time, 101– 131 µs; pulse-off time, 0–63 µs; servo voltage 0–99V; dielectric flow rate, 0–12 litre per minute (lmin^{-1}); wire feed, 1–9 m/min; wire tension, 1–9 gms. An electrode gap up to 0.5 mm has been kept between wire and work.

Table 1: Process variables and their levels

Symbol	Parameters	Levels (-1)	Levels (+1)
A	Pulse-on-time (MU)	106	116
B	Pulse-off-time (MU)	30	60
C	Current (Amp)	80	180
D	Voltage (Volt)	40	80

In the present work, wire tension and wire feed parameters were kept constant at their optimal values. Brass wire of diameter 0.25mm was used as an electrode because of its good capability to sustain high discharge energy. High flow rate results in quick and complete flushing of melted debris out of the spark gap. Therefore, dielectric flow rate is kept at maximum value of 12 l min^{-1}. Vertical cutting was performed at zero wire offset.

3. RESULTS AND DISCUSSION

The 30 experiments were conducted and CS and wire wear rate were obtained for each experimental run (as listed in Table 2).

3.1. Mathematical model for cutting speed and wire wear rate

Using the experimental data, regression equations have been developed for correlating the output performance characteristics and input WEDM parameters. ANOVA has been applied on the experimental data to select the adequate model. Design expert (DX9), a statistical tool, has been utilised to analyse the experimental data.

Table 2: Test conditions in face-centered central composite design

Run	Ton (A)	Toff (B)	Current (C)	Voltage (D)	CS	WWR	Run	Ton (A)	Toff (B)	Current (C)	Voltage (D)	CS	WWR
1	113	52	150	70	8.10113	4.0022	16	111	45	130	60	10.4628	4.1337
2	113	37	150	70	14.8516	4.2713	17	113	37	100	50	16.7458	4.2848
3	111	45	80	60	9.449	4.222	18	106	45	130	60	6.4825	4.0215
4	111	45	130	60	104896	4.1984	19	108	37	100	50	12.1993	4.266
5	116	45	130	60	14.223	4.3851	20	113	37	150	50	17.2504	4.3393
6	111	45	180	60	11.369	4.0448	21	108	37	150	50	12.1261	4.1714
7	111	45	130	60	10.2495	4.1019	22	113	37	100	70	12.9374	4.4846
8	111	30	130	60	16.545	4.385	23	111	60	130	60	4.19008	4.064
9	113	52	150	50	9.5976	4.2293	24	111	45	130	80	7.8365	4.155
10	108	52	100	70	4.5454	4.02	25	108	37	150	70	9.6923	4.188
11	113	52	100	70	7.025	4.17832	26	108	37	100	70	8.98215	4.257
12	108	52	150	70	4.9673	4.013	27	111	45	130	60	10.4628	4.1337
13	111	45	130	60	10.4896	4.1984	28	111	45	130	60	10.2495	4.1019
14	111	45	130	40	12.4904	4.201	29	108	52	150	50	6.6568	4.008
15	113	52	100	50	8.6097	4.1227	30	108	52	100	50	6.1613	4.0173

Two-factor interaction (2FI) model and Quadratic model have been suggested for CS and wire wear rate. Table 3 shows the "F-value" and "p-value" for each term in performance characteristics CS and wire wear rate. The terms having p-value less than 0.05 are considered to be significant while insignificant terms can be eliminated from the final predicted models. In case of CS, the model terms A, B, C, D, AB, AC and BD are significant. Similarly, A, B, C and CD for wire wear rate are significant.

3.1.1. Cutting speed (CS)

Final Equation in Terms of Actual Factors

Cutting Speed = –124.22029 + (1.56999 × A) + (2.14733 × B) – (0.35622 × C) – (0.27341 × D) – (0.025582 × A× B) + (3.07534E-003 × A × C) – (1.01011E-003 × A× D) + (1.09366E-005 × B× C) + (4.53964E-003 × B × D) + (5.33889E-004 × C × D)

3.1.2. Wire Wear Rate (WWR)

Final Equation in Terms of Actual Factors

Wire Wear Rate = + 30.65710 – (0.51293 × A) –(0.041405 × B) +(9.24598E-003 × C) + (0.033834 × D) + (1.68569E-005 × A × B) – (4.06416E-005 × A × C) – (1.41322E-004 × A × D) + (8.33776E-005 × B × C) – (2.53080E-004 × B × D) – (1.31042E-004 × C × D) + (2.50401E-003 × A^2) + (3.50612E-004 × B^2) – (7.38524E-006 × C^2) + (7.68656E-005 × D^2

Table 3: The ANOVA table for cutting speed

ANOVA for Response surface 2FI model						
Source	**Sum of square**	**Df**	**Mean Square**	**F-Value**	**p-Value Prob>F**	
Model	355	10	35.55	941.06	<0.0001	significant
A-Ton	84.80	1	84.80	2244.92	<0.0001	
B-Toff	255.05	1	225.05	5957.96	<0.0001	
C-current	4.61	1	4.61	121.98	<0.0001	
V-Voltage	28.46	1	28.46	753.58	<0.0001	
AB	3.74	1	3.74	98.88	<0.0001	
AC	0.61	1	0.61	16.07	0.0008	
AD	0.010	1	0.010	0.27	0.6069	
BC	6.826E-005	1	6.826E-005	1.807E-003	0.9665	
BD	1.86	1	1.86	49.17	<0.0001	
CD	0.29	1	0.29	7.65	0.0123	
Residual	0.72	0.038	0.038			
Lack of Fit	0.65	0.046	0.046	3.34	0.0946	Not significant
Pure Error	0.069	0.014	0.014			
Cor Total	356.18					

Table 4: The ANOVA table for wire wear rate

ANOVA for Response surface Quadratic model						
Source	Sum of square	Df	Mean Square	F-Value	p-Value Prob>F	
Model	0.41	14	0.030	10.17	<0.0001	**significant**
A-Ton	0.12	1	0.12	42.31	<0.0001	
B-Toff	0.19	1	0.19	66.62	<0.0001	
C-current	0.023	1	0.023	7.92	0.0131	
V-Voltage	2.54E-003	1	2.524E-003	0.87	0.3661	
AB	1.622E-006	1	1.622E-006	5.580E-004	0.9815	
AC	1.059E-004	1	1.059E-004	0.036	0.8512	
AD	2.023E-004	1	2.023E-004	0.070	0.7955	
BC	3.967E-003	1	3.967E-003	1.37	0.2609	
BD	5.773E-003	1	5.773E-003	1.99	0.1791	
CD	0.017	1	0.017	5.99	0.0272	
A2	6.878E-003	1	6.878E-003	2.37	0.1448	
B2	0.011	1	0.011	3.67	0.0746	
C2	5.983E-004	1	5.983E-004	0.21	0.6565	
D2	1.616E-003	1	1.616E-003	0.56	0.4673	
Residual	0.044	15	2.906E-003			
Lack of Fit	0.034	10	3.392E-003	1.75	0.2782	Not significant
Pure Error	9.673E-003	5	1.935E-003			
Cor Total	0.46	29				

3.2. Effect of WEDM parameters on performance characteristics

Response surface graphs (Fig. 2 and 3) have been plotted to analyze the influence of WEDM parameters on performance characteristics, namely CS, and wire wear rate. Surface plots have been plotted for combined effect of two factors.

3.2.1. Effect of WEDM parameters on cutting speed

The response surface is plotted to study the effect of process variables on the cutting rate and is shown in Fig. 2a and 2b. From Fig. 2a, MRR is found to have an increasing trend with the increase of pulse on time. At the same time, it decreases with the increase of pulse off time. This establishes the fact that MRR is proportional to the energy consumed during machining and is dependent not only on the energy contained in a pulse determining the crater size, but also on the applied energy rate or power. It is observed from Fig. 2b that MRR increases with increase in current but at slow rate and it also increases with increase in T_{on}. The higher is the current setting, the larger is the thermal effect during the on time. This leads to increase in MRR. But, the sensitivity of the current setting on the cutting performance is stronger than that of the pulse on time. While the peak current setting is too high, wire breakage occurs frequently.

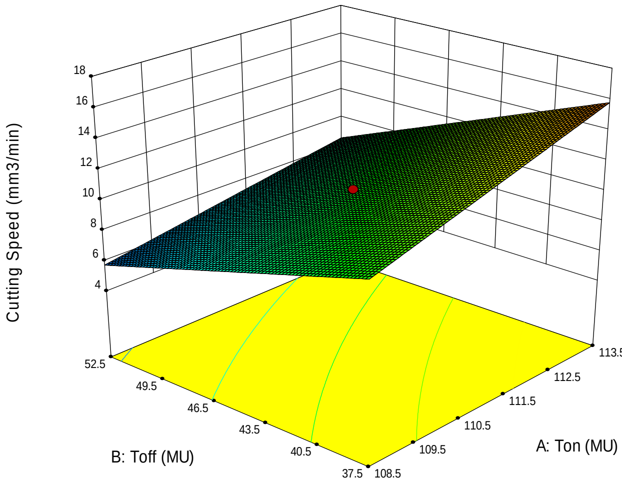

Fig. 2a: Combined effect of T_{on} and T_{off} on CS

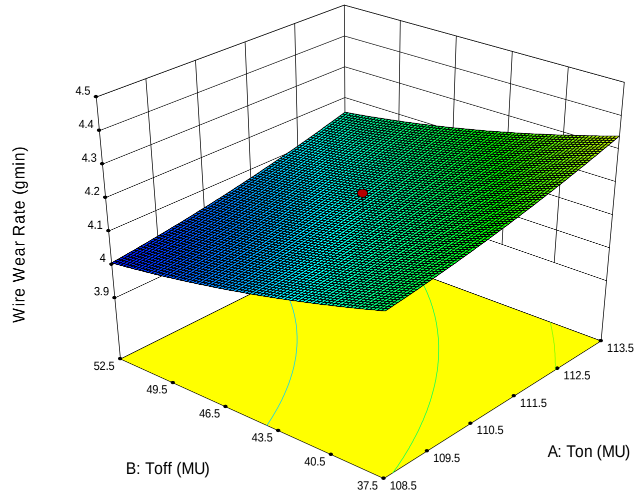

Fig. 3a: Combined effect of T_{on} and T_{off} on WWR

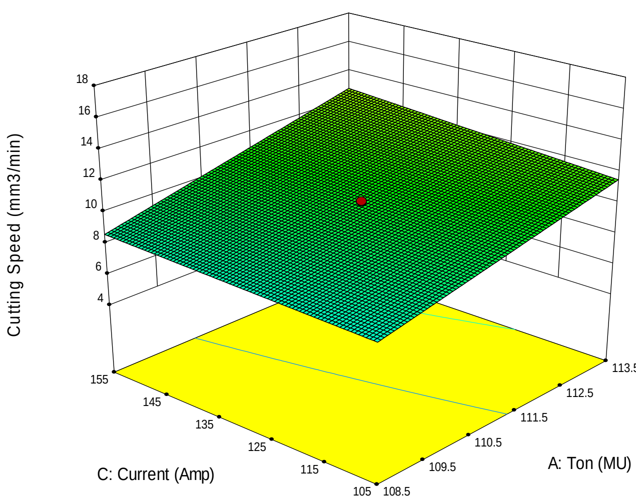

Fig. 2b: Combined effect of T_{on} and current on CS

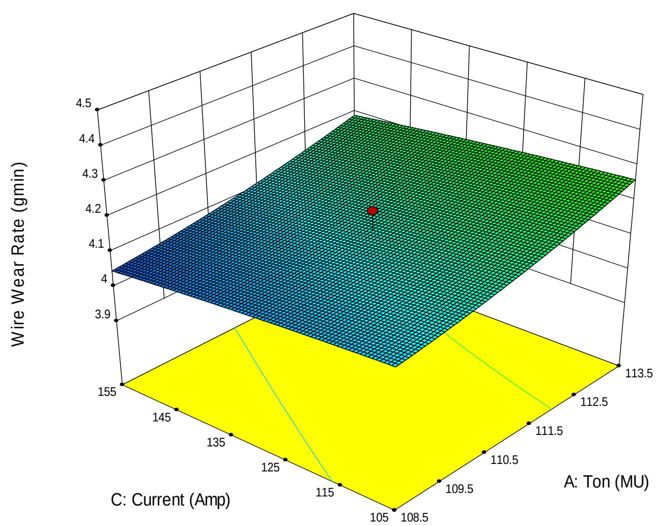

Fig. 3b: Combined effect of Ton and current on WWR

3.2.2. Effect of WEDM parameters on wire wear rate

The response surface is plotted to study the effect of process variables on the wire wear rate as shown in Figures 3a and 3b. From Fig. 3a, it is seen that the wire wear rate increases with increase in pulse on time while WWR decreases with increase in value of pulse off time. It is obvious that due to increase in value of pulse on time, higher amount of discharge energy will be supplied and cutting rate will also increase due to which wire wear rate will also increase. From Fig. 3b, it is clear that with the increased value of pulse on time WWR gets increased. However, the increase in current results in the reduction in WWR. This might be attributed to the fact that the higher thermal effect (due to increased current) results in severe evaporation of the wire electrode, which increases its wear, but the wire consumption is reduced as the lesser quantity (length) of wire is used for the same cross-section area of the work sample.

4. OPTIMIZATION USING DESIRABILITY FUNCTION

Derringer and Suich (1980) described a multiple response method called desirability. It is an attractive and user friendly method for industry for optimization of multiple response characteristics problems. The method makes use of an objective function, D(X), called the desirability function and transforms an estimated response into a scale free value (di) called desirability. The desirable ranges are from zero to one (least to most desirable respectively). The factor settings with maximum total desirability are considered to be the optimal parameter conditions. The simultaneous objective function is a geometric mean of all transformed responses.

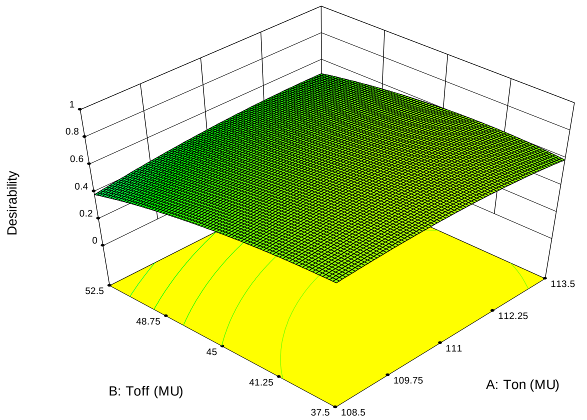

Fig. 4: Desirability plot for maximum cutting speed and WWR

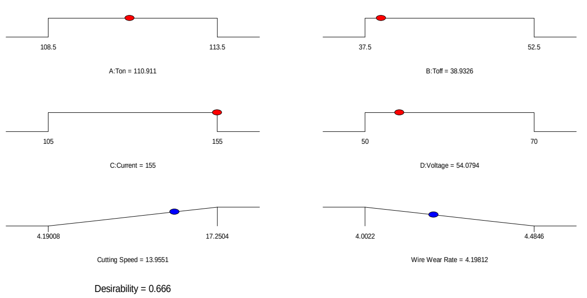

Fig. 5: Ramp graph for Max. Desirability (0.666)

5. CONCLUSIONS

In present work, the effect of machining parameters of WEDM on the response variables such as material removal rate MRR and wire wear rate on the material (WC-24%Co) has been discussed. Also the optimal levels of the machining parameters for each of response variables have been found out using response surface methodology (RSM). The important conclusions drawn from the present study are summarized below:

- For material removal rate, Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D) and some of the interactions (AB, BD) have been found to be significant (at 95% confidence level) for MRR. P value (0.0001) is same for all the four factors. The higher is the current setting, higher the MRR. But, the sensitivity of the current setting on the cutting performance is stronger than that of pulse on time.
- For wire wear rate, Pulse on time (A), pulse off time (B), peak current (C) are the significant factors. P value (0.0001) is same for all the three factors. In addition, Pulse off time (B) is also significant factor for wire wear rate. WWR gets decreased with increase in spark voltage, current and pulse off time.

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