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Modeling and investigating for Cutting Speed and Dimensional Deviation in WEDM of WC-24% Co Composite using Response Surface Methodology and Desirability Function

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Abstract

Wire electrical discharge machining (WEDM) is well known process for machining hard metal alloys and metal matrix composites. The present work is undertaken on 24% cobalt and 76% tungsten carbide using L30 orthogonal array. In this paper, four important WEDM parameters namely pulse-on-time, pulse-off-time, voltage and current has been investigated and modeled for machining of WC-24%Co composite during cutting speed operation on WEDM. Using response surface methodology, face centered central composite design has been adopted to perform the experiments. The level of significance of the machining parameter for their effect on cutting speed and dimensional deviation was determined by using analysis of variance (ANOVA). Achieving higher machining speed is the main objective of rough cutting operation. Therefore, using desirability function, parameters have been predicted for maximizing the machining cutting speed and minimizing the dimensional deviation.

Keywords: WEDM, WC-24%Co composite, Cutting Speed, Dimension Deviation, Response Surface Methodology, Desirability Function.

INTRODUCTION

Tungsten, titanium, and chromium carbide are known for their hardness and wear resistance properties, which makes them useful materials for cutting tool applications. Tungsten carbide combined with a metallic binder such as cobalt is called as a cemented carbide or cermet (WC). Due to the high material hardness, advanced ceramics such as WC are difficult to machine using conventional machining processes such as milling, turning, and grinding. In recent years, as an alternative method to machine WC, wire electrical discharge machining (WEDM) has gained wide acceptance. Wire electrical discharge machining is an emerging nonconventional machining process for machining hard to machine materials that are electrically conductive. In this process, the material is removed by a series of discrete electrical discharges between the wire electrode and the work piece. The discharges, which are highly focused by the dielectric medium, cause rise in the local temperatures of the work piece near the point of introduction. The temperatures are high enough to melt and vaporize the material in the immediate vicinity of the electrical discharges. The most important machining response of the process is cutting speed or material removal rate. This article discusses in detail the machining of tungsten carbide cermet using WEDM. The WC used in this article has 76% WC and 24% cobalt. In order to achieve high productivity within specified tolerance on WEDM, selection of optimal process parameters plays a key role which depends on large numbers of variables such as composition and grain sizes of work material, machining parameters, wire electrode material, wire diameter, cutting condition and work geometry. Figure 1 represents the schematic diagram of WEDM.

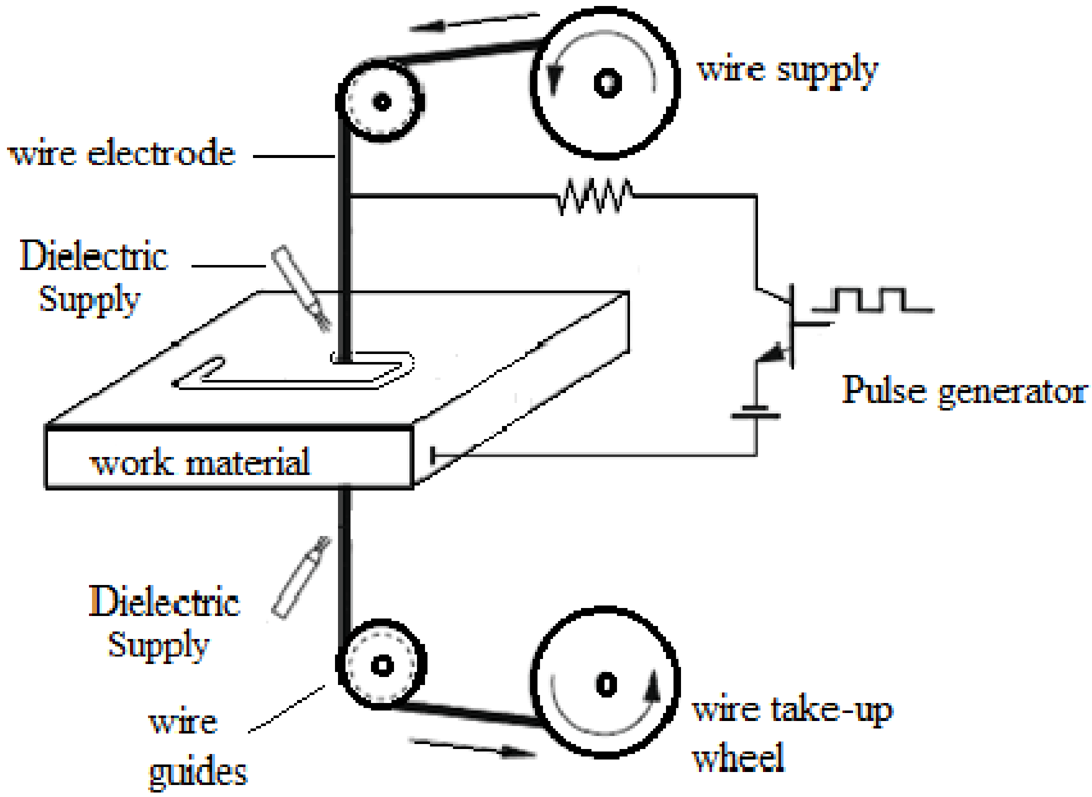

Figure 1 Schematic Representation of WEDM

Influence of composition and grain size of WC-based cermets on machinability by WEDM has been studied by Lauwers et al. (2006). It was shown that the cutting rate decreases with increasing grain size and cobalt percentage, which can be explained mainly by the change in thermal conductivity of the. Jangra et al. (2011a) evaluated the effect of various factors and their sub-factors on machinability of WC-Co composite with WEDM using digraph and matrix method. They broadly grouped these factors into work material, machine tool, tool electrode, cutting conditions and geometry to be machined. Machinability was measured in terms of material removal rate (MRR). They concluded that the machine tool is the most influencing factor affecting the machinability of WC-Co composite. Jangra et al. (2012) optimized the multi machining characteristics in WEDM of WC-5.3%Co composite using an integrated approach of Taguchi, GRA and entropy method. Six input parameter- taper angle, discharge current, pulse-on time, pulse-off time, wire tension and dielectric flow rate were investigated for four output machining characteristics: MRR, SR, RoC and angular error. Hewidy et al. (2005) investigated that the effect of input parameters like peak current, duty factor, wire tension and water pressure on the metal removal rate, wear ratio and surface roughness while machining of Inconel 601 with WEDM using RSM. They concluded that the volumetric metal removal rate generally increase with increase of peak current value and water pressure.. Assarzadeh and Ghoreishi (2013) investigated the effect of input parameters like discharge current (A: Amp), pulse-on time (B: μs), duty cycle (C: %), and gap voltage (D: Volt) on the material removal rate (MRR: mm3/min), tool wear rate (TWR: mm3/min), and average surface roughness while machining of WC-6%Co composite with EDM. 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. Kanalayasiri and Boonmung (2007) reported the application of WEDM process for machining newly developed DC 53 die steel and revealed that surface roughness increase with pulse on time and peak current.

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 (Ton), 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 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.Input parameter levels selected and their ranges

Symbol	Parameters	Levels (-1)	(+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.

2.2 Experimental design using RSM

Based upon the input factors and their levels as listed in Table 1, the experimental plan was designed on the basis of standard RSM design called face centered Central Composite Design (CCD

Table 2. Different testing values in face centered central composite design for four parameters

Std	Run	Factor 1 A:Ton (MU)	Factor 2 B:Toff (MU)	Factor 3 C:current (Amp)	Factor 4 D:Voltage (volt)	Response 1 Mean cutting speed (mm/min)	Response 2 Dimensional deviation (mm)
16	1	113	52	150	70	0.31	0.061
14	2	113	37	150	70	0.55	0.07
21	3	111	45	80	60	0.338	0.071
25	4	111	45	130	60	0.389	0.0715
18	5	116	45	130	60	0.546	0.056
22	6	111	45	180	60	0.432	0.0685
27	7	111	45	130	60	0.3922	0.062
19	8	111	30	130	60	0.63	0.072
8	9	113	52	150	50	0.394	0.0745
11	10	108	52	100	70	0.17	0.0565
12	11	113	52	100	70	0.25	0.065
15	12	108	52	150	70	0.186	0.055
28	13	111	45	130	60	0.394	0.072
23	14	111	45	130	40	0.47	0.0815
4	15	113	52	100	50	0.331	0.066
29	16	111	45	130	60	0.387	0.066

2	17	113	37	100	50	0.613	0.078
17	18	106	45	130	60	0.243	0.056
1	19	108	37	100	50	0.434	0.074
6	20	113	37	150	50	0.655	0.0705
5	21	108	37	150	50	0.434	0.0885
10	22	113	37	100	70	0.49	0.063
20	23	111	60	130	60	0.167	0.0535
24	24	111	45	130	80	0.302	0.046
13	25	108	37	150	70	0.363	0.0625
9	26	108	37	100	70	0.363	0.0805
26	27	111	45	130	60	0.387	0.065
30	28	111	45	130	60	0.395	0.063
7	29	108	52	150	50	0.25	0.06
3	30	108	52	100	50	0.22	0.0765

3. Modelling using ANOVA of WEDM Parameters

Using the experimental data, regression equations has been developed for correlating the machining speed (MS) and input WEDM parameters. Design expert (DX9), a statistical tool, has been utilised to analyse the experimental data. Using Analysis of Variance (ANOVA), quadratic Vs two factors interaction (2FI) model has been suggested for machining speed. Table 3 shows the summary of fitted model. Adequacy of the results can be analysed by residual plots (Kanlayasiria and Boonmung, 2007). Figure 2 shows that the residuals are normally distributed about a straight line.

Table 3a ANOVA table for Mean Cutting Speed

ANOVA for Response Surface 2FI model						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.50	10	0.050	1210.67	< 0.0001	significant
Residual	7.824E-004	19	4.118E-005			
Lack of Fit	7.205E-004	14	5.146E-005	4.16	0.0622	not significant
Pure Error	6.190E-005	5	1.238E-005			
Cor Total	0.50	29				

Regression equation in terms of coded factors:

Cutting speed= +0.39+ 0.075*A- 0.11*B+ 0.021*C- 0.042*D- 0.016* AB+ 0.012*AC- 8.750E-003*AD + 4.187E-003* BC + 5.685E-003*BD + 5.494E-005*CD (1)

Regression equation in terms of actual factors

Cutting speed = -5.65991 +0.065008 * Ton +0.071974 * Toff -0.020697 * current +0.030419 * Voltage -8.53326E-004 * Ton * Toff +1.84884E-004 * Ton * current -3.42803E-004 * Ton * Voltage +2.23302E-005 * Toff * current +7.57997E-005 * Toff * Voltage +2.19741E-007 * current * Voltage (2)

Table 3b. ANOVA analysis values for Mean cutting Speed

Std. Dev.	6.417E-003	R-Squared	0.9984
Mean	0.38	Adj R-Squared	0.9976
C.V. %	1.68	Pred R-Squared	0.9950

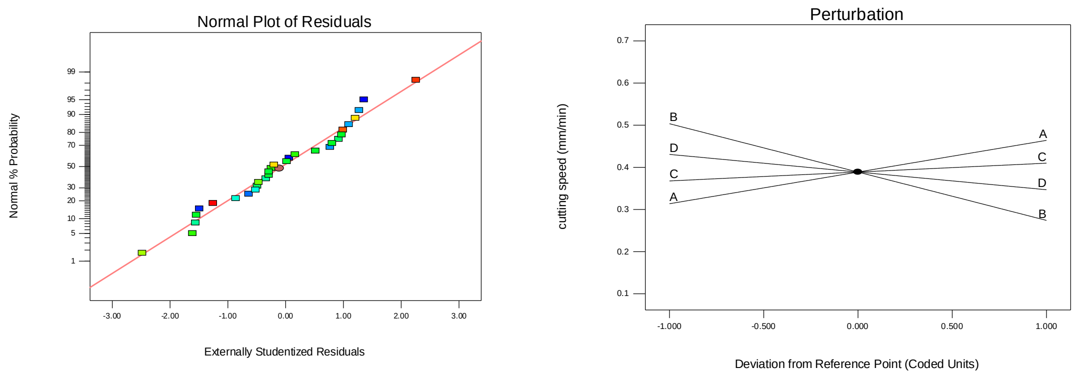

Figure 2a Normal probability plot of residuals for CS and Perturbation graph

The significant factors A, B, C, D, AB, AC, AD, BC, BD. Values of ''p-value>F'' less than 0.0500 shows model terms are statistically significant at 95% confidence level. Perturbation curve shows the effect of each process input parameter on mean cutting speed with a common point where all four input parameters meats to achieve max. mean cutting speed.

Table 3c. ANOVA Table for Dimensional Deviation

ANOVA for Response Surface 2FI model						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	1.630E-003	10	1.630E-004	3.29	0.0124	significant
Residual	9.421E-004	19	4.958E-005			
Lack of Fit	8.519E-004	14	6.085E-005	3.37	0.0931	not significant
Pure Error	9.021E-005	5	1.804E-005			
Cor Total	2.572E-003	29				

Final Equation in Terms of Coded Factors:
Dimensional deviation = +0.067 -1.314E-004 * A -4.374E-003 * B -9.838E-004 * C -6.160E-003 * D +2.613E-003 * AB +1.574E-003 * AC +6.347E-004 * AD -6.297E-004 * BC -3.718E-004 * BD -1.240E-003* CD

Final Equation in Terms of Actual Factors:
Dimensional deviation = +1.29755 -0.011121 * Ton -0.015317 * Toff -2.38651E-003 * current -2.56616E-003 * Voltage +1.39345E-004 * Ton * Toff +2.51888E-005 * Ton * current +2.53890E-005 * Ton * Voltage -3.35838E-006 * Toff * current -4.95677E-006 * Toff * Voltage -4.96110E-006 * current * Voltage

Table 3d. ANOVA Table for Dimensional Deviation

Std. Dev.	7.042E-003		R-Squared	0.6337
Mean	0.067		Adj R-Squared	0.4409
C.V. %	10.53		Pred R-Squared	-0.4304
PRESS	3.679E-003		Adeq Precision	7.910

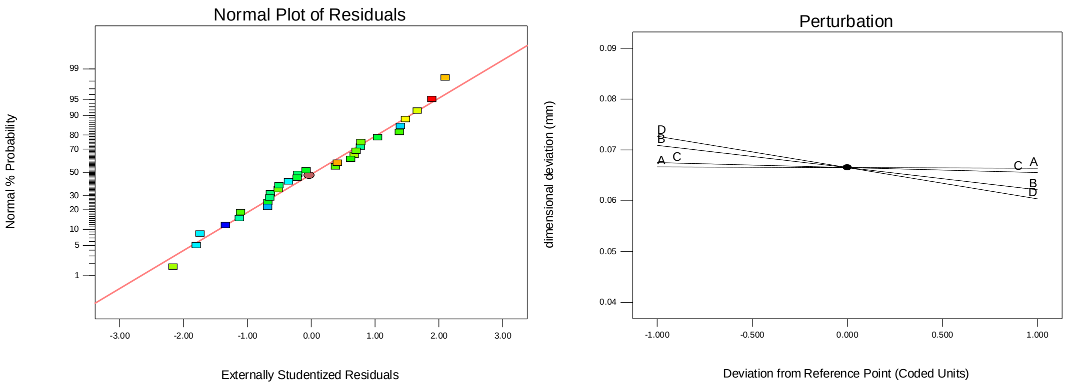

Figure 2b Normal probability plot of residuals for Dimensional Deviation and Perturbation graph

The significant factors are B and D which is also confirmed from perturbation curve. Values of ‘‘p-value>F’’ less than 0.0500 shows model terms are statistically significant at 95% confidence level. Perturbation curve shows the effect of each process input parameter on mean cutting speed with a common point where all four input parameters meats to achieve minimum dimensional deviation.

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.

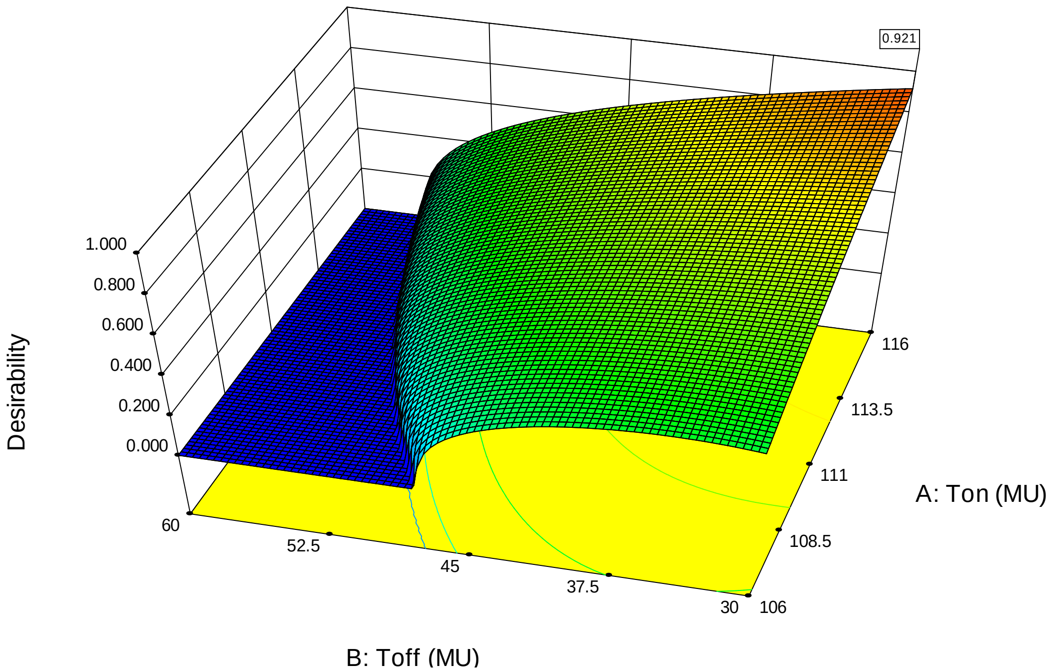

Fig. 3a. Desirability plot for maximum desirability

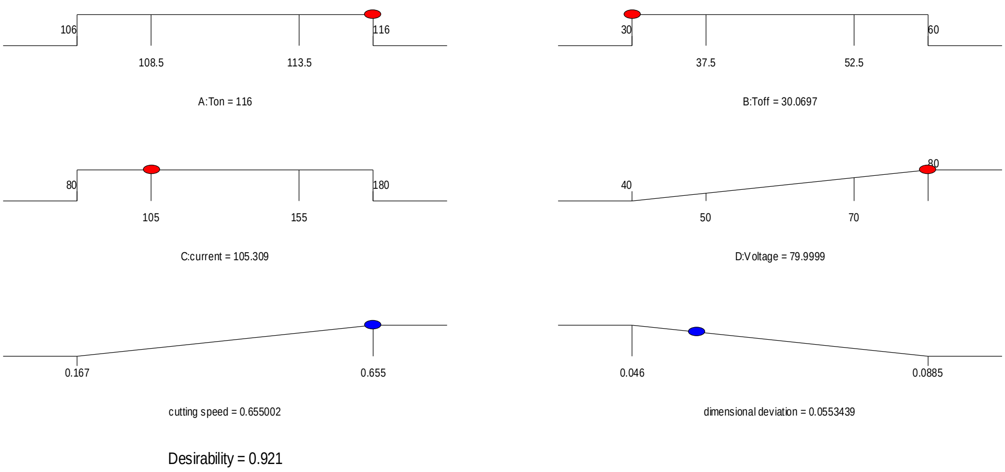

Fig. 3b. Ramp graph for Max. Desirability (0.921)]

4.1 Optimal Solution

The goal of optimization is to find a good set of conditions that will meet the desired goal. It is not necessary that the value of desirability is always 1.0 as the value is completely dependent on how closely the lower and upper limits are set relative to the actual optimum value. The set of conditions possessing highest desirability value have been selected as optimum conditions for maximum cutting speed and minimum dimensional deviation. The constraints for the optimization of cutting speed have been shown in fig 3b by the help of ramp chart. Using Design expert (DX-9), optimal solutions have been derived for specified design space constraints for machining speed. Table 4 shows the set of conditions correspond to maximum desirability value for CS and minimum dimensional deviation. Figure 3a shows the 3D surface plot for desirability. Fig 2 shows the Normal probability plot of residuals for CS and perturbation curve.

5. Conclusion

Quadratic Vs two factors interaction (2FI) has been found the best fit model for cutting speed. From perturbation curve, it is clear that cutting speed increases with increase in value of T_{on} and current while T_{on} and current do not have major effect on dimensional deviation. Dimensional deviation decreases with increase in voltage and $T_{off.}$ Using desirability function, parameters have been predicted for maximizing the machining speed and minimize dimensional deviation. Optimal values of those are shown below in table 4.

Table 4. Optimal conditions for best results

S.No.	T_{on}	T_{off}	current	voltage	Cutting speed	Dimensional deviation
1	116	30.0697	105.309	69.9998	0.6550	0.05553

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