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Multi Parametric Optimization of WC-24%Co Composite Material using Desirability Approach

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Abstract—*Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. This practical technology of the WEDM process is based on the conventional EDM sparking phenomenon utilizing the widely accepted non-contact technique of material removal. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality. Present study has been made to optimize the process parameters during machining of tungsten carbide cobalt (WC-24%Co) by wire electrical discharge machining (WEDM) using response surface methodology (RSM). Four input process parameters of WEDM (namely servo voltage (V), pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and current (A)) were chosen as variables to study the process performance in terms of cutting speed. 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.*

Keyword*: WEDM, WC-24%Co composite, Cutting Speed, Response Surface Methodology, Desirability Function.*

1. INTRODUCTION

Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. It is considered as a unique adaptation of the conventional EDM process, which uses an electrode to initialize the sparking process. However, WEDM utilises a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05–0.3 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 workpiece and the wire, eliminating the mechanical stresses during machining. In addition, the WEDM process is able to machine exotic and high strength and temperature resistive (HSTR) materials and eliminate the geometrical changes occurring in the machining of heat-treated steels.

Several attempts have been made to determine optimal machining conditions for WC-Co composite on EDM and WEDM. Scot et al. presented a formulation and solution for the multi-objective optimization problem for the selection of the best control settings parameters for the wire electrical discharge machining process. It was found that discharge current, pulse duration and pulse frequency were the main significant control factors for both the metal removal rate (MRR) and surface finish, while wire speed, wire tension and dielectric flow rate were relatively significant. Trang et al. utilized a neural network to model the WEDM process to assess the optimal cutting parameters using an adjustable objective function. Two models were designed by Spedding and Wang with input parameters of the pulse width, the time between the successive pulses and the wire mechanical tension, whilst cutting speed, surface roughness and surface waviness were the responses. It was concluded that both models provide accurate results for the process. Hsue et al. developed model to estimate the MRR in the corner cutting. They showed a good agreement between the computed MRR and the measured sparking frequency of the process.Liao et al. proposed a methodology to determine the optimal working parameters. The significant factors affectingthe machining performance such as MRR, gap width, surface roughness, sparkingfrequency, average gap voltage and ratio of normal sparks to total sparks were determined. They concluded that the machining models are appropriate and the derived machining parameters satisfy the real requirements in practice. 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. 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. EXPERIMENTATION

Figs. 1 and 2show the schematic diagram and the set-up of the WEDM process. It is an advanced material removal process using a thin copper wire as the tool electrode. The workpiece and electrode are separated by dielectric medium (kerosene–deionized water). The travelling of the wire, in a closely controlled manner, through the workpiece, generates spark discharges and then erodes the workpiece to produce the desired shape (based on the path of the tool electrode).

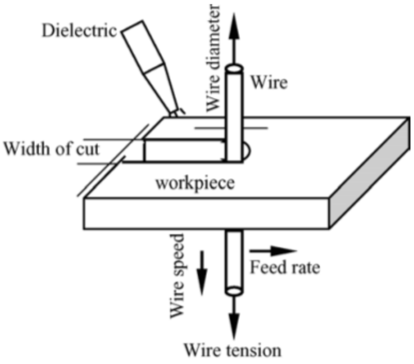

Fig. 1: Wire EDM Process

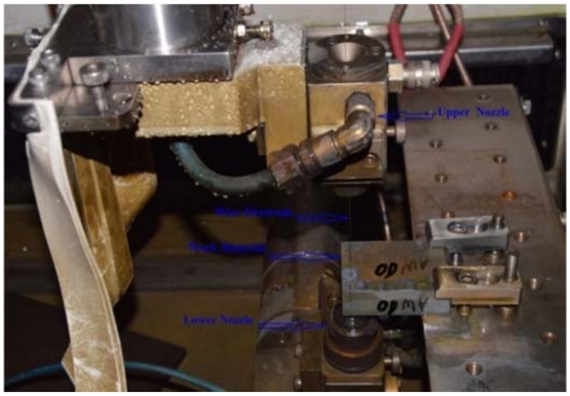

Fig. 2: Wire EDM setup

Table 1: Levels of process parameters

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

The machining experiments were performed on an ELEKTRA SPRINTCUT 734wire electrical discharge machine. Experiments were carried out by pulse arc discharges generated between wire (brass with 0.25mm in diameter) and the tungsten carbide cobalt composite (WC-24%Co) workpiece (70×50×20 mm size).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.

Table 2: Test conditions in face centered central composite design for four parameters

Std.	Factor 1 Ton (MU)	Factor 2 Toff (MU)	Factor 3 Current (Amp).	Factor4 Voltage (volt)	Response Mean Cutting speed (mm/min)	Std.	Factor 1 Ton (MU)	Factor 2 Toff (MU)	Factor 3 Current (Amp).	Factor4 Voltage (volt)	Mean Cutting speed (mm/min)
16	113	52	150	70	0.31	29	111	45	130	60	0.387
14	113	37	150	70	0.55	2	113	37	100	50	0.613
21	111	45	80	60	0.338	17	106	45	130	60	0.243
25	111	45	130	60	0.389	1	108	37	100	50	0.434
18	116	45	130	60	0.546	6	113	37	150	50	0.655
22	111	45	180	60	0.432	5	108	37	150	50	0.434
27	111	45	130	60	0.3922	10	113	37	100	70	0.49
19	111	30	130	60	0.63	20	111	60	130	60	0.167
8	113	52	150	50	0.394	24	111	45	130	80	0.302
11	108	52	100	70	0.17	13	108	37	150	70	0.363
12	113	52	100	70	0.25	9	108	37	100	70	0.363
15	108	52	150	70	0.186	26	111	45	130	60	0.387
28	111	45	130	60	0.394	30	111	45	130	60	0.395
23	111	45	130	40	0.47	7	108	52	150	50	0.25
4	113	52	100	50	0.331	3	108	52	100	50	0.22

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 central composite design with 4 parameters at 3 levels and 30 experimental runs. The experimental plan, levels selected and their range is given in Table 1.

3. RESULTS AND DISCUSSION

The 30 experiments were conducted and cutting speed (CS) was obtained for each experimental run (as listed in Table 2).

3.1 Modeling Response Variables

Tables 3 and Table 4 show the variance analysis results of the RSM models for cutting speed. The associated P value for significant. It also shows the value of R^2-statistic and adjusted R^2-statistic. The R Squared (R^2) is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit. The more R^2approaches unity, the better model fits the experimental data. For instance, the obtained value of 0.9984 for R^2implies that the model explains approximately 99.84%of the variability in cutting speed, whereas R^2 adjusted for the model is 0.9984.

Table 3: ANOVA table for fitted model

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				

Table 4.Variance analysis for the model of 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

Table 5 presents the values of coefficients of model. Values of ‘‘p-value>F’’ less than 0.0500 indicate model terms are significant at 95% confidence level for cutting speed. According to Table 5, A, B, C, D, AB, AC, AD, BC, BDare the significant factors. The final response equations cutting speed is found as follow:

Table 5: The effect of pulse-on time, pulse-off time, voltage and current on cutting speed

ANOVA for Response Surface 2FI model						
	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	0.50	10	0.050	1210.67	< 0.0001	**Significant**
A-Ton1	0.13	1	0.13	3241.97	< 0.0001	**Significant**
B-Toff	0.30	1	0.30	7300.27	< 0.0001	**Significant**
C-current	0.010	1	0.010	254.96	< 0.0001	**Significant**
D-Voltage	0.040	1	0.040	971.25	< 0.0001	**Significant**
AB	4.156E-003	1	4.156E-003	100.92	< 0.0001	**Significant**
AC	2.193E-003	1	2.193E-003	53.27	< 0.0001	**Significant**
AD	1.191E-003	1	1.191E-003	28.91	< 0.0001	**Significant**
BC	2.846E-004	1	2.846E-004	6.91	0.0165	**Significant**
BD	5.178E-004	1	5.178E-004	12.58	0.0022	**Significant**
CD	4.892E-008	1	4.892E-008	1.188E-003	0.9729	
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 Actual factors

$$\text{Cutting speed} = -5.65991 + 0.065008 \times T_{on} + 0.071974 \times T_{off} - 0.020697 \times \text{current} + 0.030419 \times \text{Voltage} - 8.53326E\text{-}004 \times T_{on} \times T_{off} + 1.84884E\text{-}004 \times T_{on} \times \text{current} - 3.42803E\text{-}004 \times T_{on} \times \text{Voltage} + 2.23302E\text{-}005 \times T_{off} \times \text{current} + 7.57997E\text{-}005 \times T_{off} \times \text{Voltage} + 2.19741E\text{-}007 \times \text{current} \times \text{Voltage} \quad (1)$$

3.2 Effects of input process 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. 3a and 3b. From Fig. 3a, 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. 3b 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 ontime. While the peak current setting is too high, wire breakage occurs frequently.

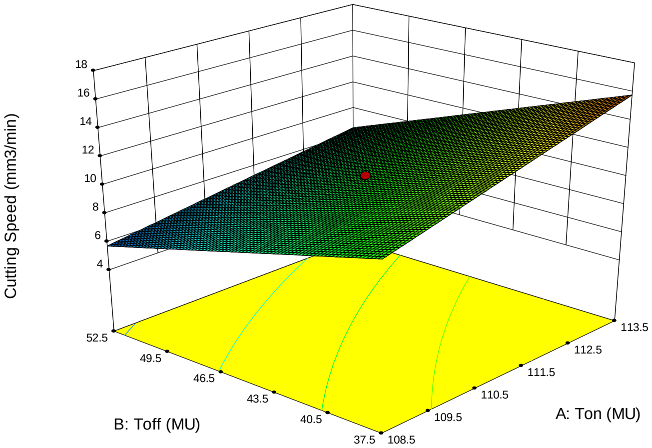

Fig. 3a: Combined effect of Ton and T_{off} on CS

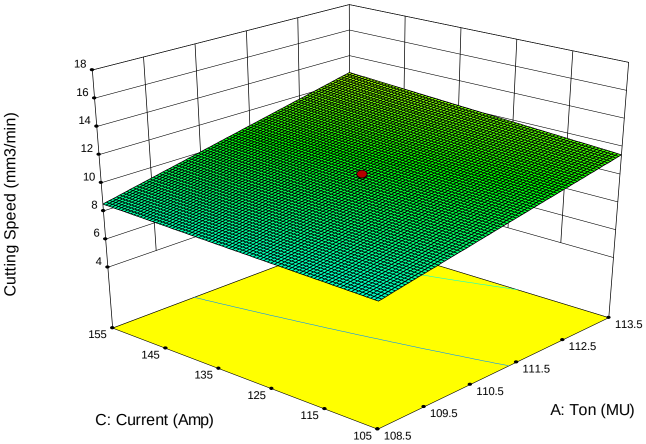

Fig. 3b: Combined effect of Ton and current on CS

4. OPTIMIZATION OF RESPONSE PARAMETERS

Optimization of cutting speed was performed separately for achieving the desired cutting speed based on the developed mathematical model (i.e. equation (1)).The value of composite desirability D, was takenas 0 to 1. The optimized response value of cutting speed is 0.905 mm.

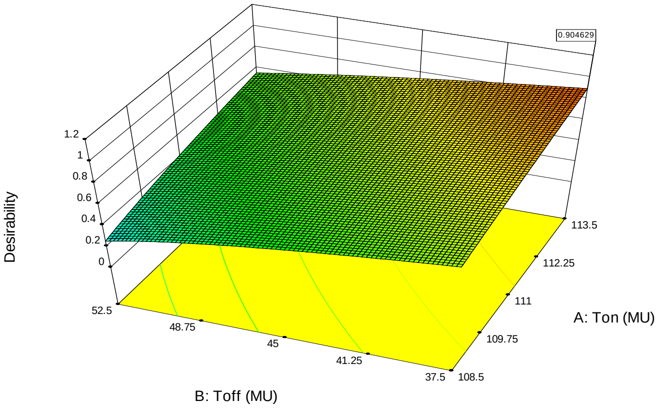

Fig. 4: Desirability plot for maximum cutting speed

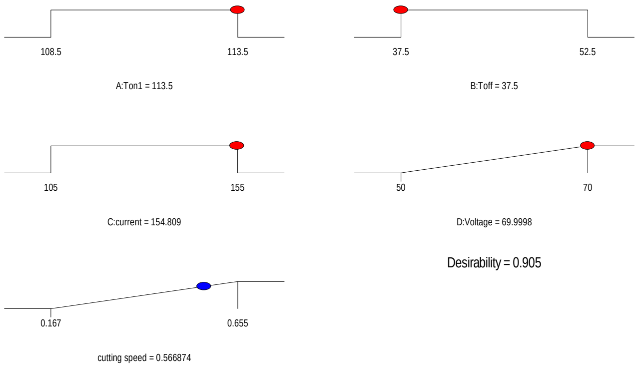

Fig. 5: Ramp graph for Max. Desirability (0.9050)

5. CONCLUSION

In the present research work, the 2FI model for metal removal rate has been developed to correlate the dominant machining parameters: pulse on time, pulse off time, peak current and spark gap voltage in the WEDM process of tungsten carbide cobalt composite (WC-24%Co) material. An experimental plan of the central composite design based on the RSM has been applied to perform the experimentation work. The machinability evaluation in the WEDM process has been analyzed according to the developed mathematical model to obtain the following conclusions:

1. For cutting speed, Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D) and some of the interactions (AB, AC, AD, BC, BD) have been found to be significant (at 95% confidence level) for cutting speed (CS). The higher is the current setting and pulse on time, higher the cutting speed.
2. From perturbation curve, it is clear that cutting speed increases with increase in value of T_{on} and current.

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