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Experimental Investigation and Modelling of Wire Electrical Discharge Machining Process on W-Cu Metal Matrix Composite

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Abstract

Tungsten-Copper (W-Cu) metal matrix composites (MMCs) have been used in thermal and electrical applications over last two decades. The machining of such multi-functional material with conventional machining methods is not economical because of its micro structural properties. This paper discusses experimental exploration of wire electrical discharge machining (WEDM) of W-Cu metal matrix composite on material removal rate (MRR). Experiments are conducted according to central composite design (CCD). Furthermore, response surface methodology (RSM) has been employed for modelling and investigating the effects of process parameters: Pulse on time (Ton), Pulse off time (Toff), Peak current (IP), Wire tension WT) and Spark gap voltage (SV) on MRR. Subsequently, analysis of machining of W-Cu MMC in WEDM is made based on the developed model. Furthermore, the model has been verified and checked for its adequacy.

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Keywords: CCD; MRR; RSM; W-Cu composite; WEDM.

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1. Introduction

WEDM is a nonconventional stochastic process in which heat energy of a spark is used to remove material from the workpiece using a wire. The basic requirement for WEDM is that both the wire and the work piece should be electrically conductive. Furthermore, material removal process in WEDM is by means of a series of discrete sparking between the wire and the work material in the presence of a dielectric fluid. Consequently, the material erosion mechanism primarily makes use of electrical energy and turns it into thermal energy through a series of

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discrete electrical discharges occurring between the electrode and work piece through dielectric medium [1, 2]. Since the introduction of the process, WEDM has evolved as 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 [3].

W-Cu sintered composite materials are used in different applications as well as for electrode materials of electrical discharge machining (EDM) for machining of die steel and tungsten carbide workpiece. Furthermore, the microstructure properties of W-Cu make the cutting process more difficult to be machined with conventional machining methods [4, 5]. As, W-Cu electrode is more costly than conventional electrodes, there is a need to understand the machinability aspects of this material [6]. The literature reveals that the machinability aspects of W-Cu MMC have not been fully explored [7]. Therefore, the authors investigate machinability aspects of W-Cu MMC in WEDM. This work summarizes: Experimental investigation of significant parameters affecting MRR; formulation of different empirical models for MRR considering analysis of variance (ANOVA) along with response surface analysis of mathematical modelling; comparing developed empirical models based on absolute mean prediction error and selecting an adequate model for MRR.

Nomenclature

Ton	pulse on time
Toff	pulse off time
IP	peak current
WT	wire tension
SV	gap voltage
y_P	predicted response
y_E	experimental response

2 Materials and Method

2.1 Materials and Machine Tool Used

The present work uses W-30Cu MMC as work material fabricated using powder metallurgy (P/M) (directly procured). The hardness, conductivity and density of material are 91-92 HRB, 41 %IACS and 13.6 g/cm^3 respectively. The material is cut on CNC WEDM with brass wire of 0.25 mm diameter in the presence of de-ionized water as dielectric fluid. All the experiments have been conducted on CNC WEDM of Electronica Machine Tools. The machine is having a CNC controller of EMT 100W-5 and simultaneous control over X, Y, u, v axes.

2.2 *Experimental Work*

On the basis of exploratory experiments, literature survey and referring machine tool manual, the different WEDM process variables affecting the MRR have been identified as Ton, Toff, IP, WT and SV. Consequently, the experiments are conducted using central composite design (CCD). This design is capable of fitting up to the second order model including the quadratic terms. According to this design, 52 experimental tests were conducted, including five levels for each variable with 32 factorial points, 10 center points in a cube and 10 axial points. During each trial, 6 mm by 6 mm workpiece of 5 mm thick is cut on CNC WEDM. MRR is calculated by the weight difference method and given by Eq. (1).

$$\mathrm{MRR} = \frac{\text{Mass before machining} - \text{Mass after machining}}{\text{Machining time}} \tag{1}$$

3 Results and Discussion

3.1 Formulation of Adequate Empirical Model

The literature reveals that first or second order polynomial can model WEDM process adequately. Therefore, investigations were made using RSM to find the mathematical regression models for MRR using the data collected while machining. Interactions of the input parameters were also noted and studied. Using MINITAB 16, different empirical models have been created for MRR. Subsequently, the adequacy of the models has been analysed using sequential the model sum of squares, lack of fit test and model summary statistics for material removal rate. Moreover, the ANOVA was performed statistically to analyse the results. Each of the created models has been checked for absolute mean prediction error calculated using Eq. (2).

$$\text{Absolute Mean Predictive Error} = \left| \frac{1}{N} \sum_{1}^{N} \frac{(y_E - y_P)}{y_E} \times 100 \right| \qquad (2)$$

Where, N is the total number of experimental data points, y_E and y_P are the experimental and predicted response values.

Table 1. Absolute mean predictive error for MRR

Sr. No.	Model	Absolute mean predictive error
1	Linear	1.26 %
2	Linear + Interaction Terms	**0.52 %**
3	Linear + Interaction Terms + Square Terms	0.80 %
4	Non- linear Model	4.60%

Table 1 depicts the absolute mean predicted error for different developed empirical models. It is seen that the linear model with interaction terms has least absolute mean predictive error as compared to the other models. Consequently, this model has been selected to model the MRR. In addition, the predicted MRR is compared with some experimentally observed values, the results of which are shown in Fig. 1. It is seen that the predicted MRR is in good agreement with most of the experimentally observed MRR. Therefore, the selected model is used for further analysis.

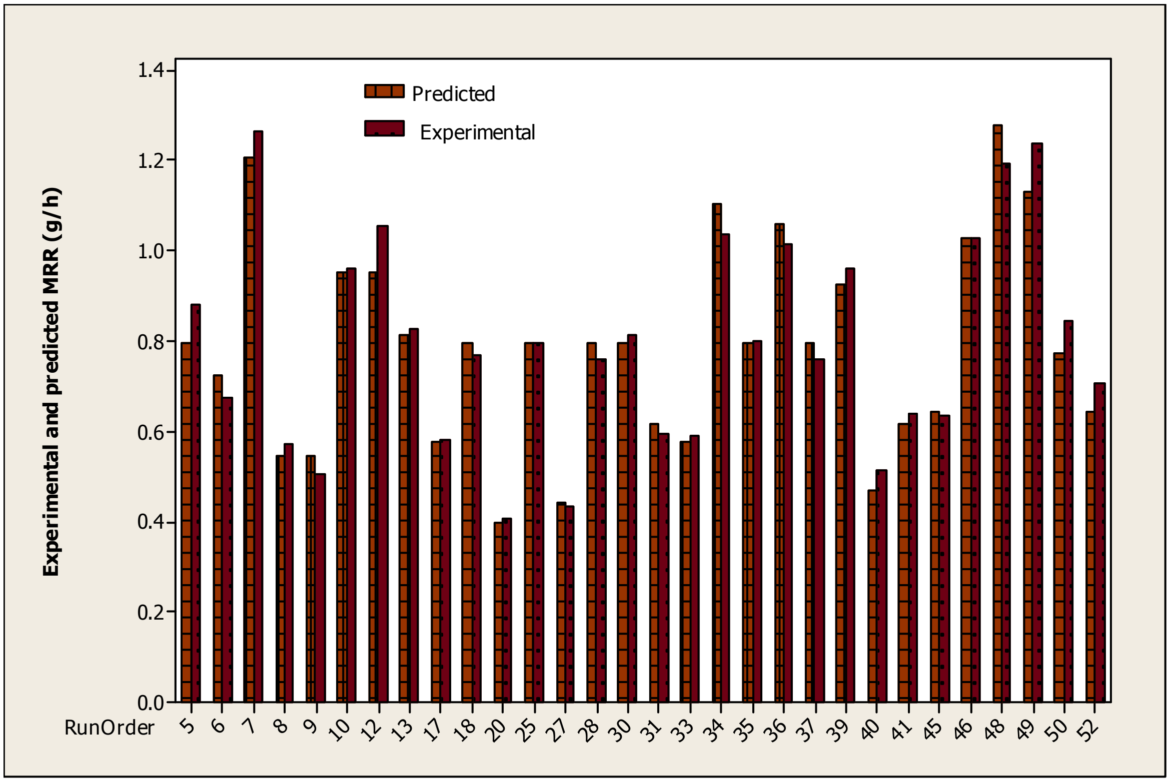

Fig. 1. Predicted and experimental MRR

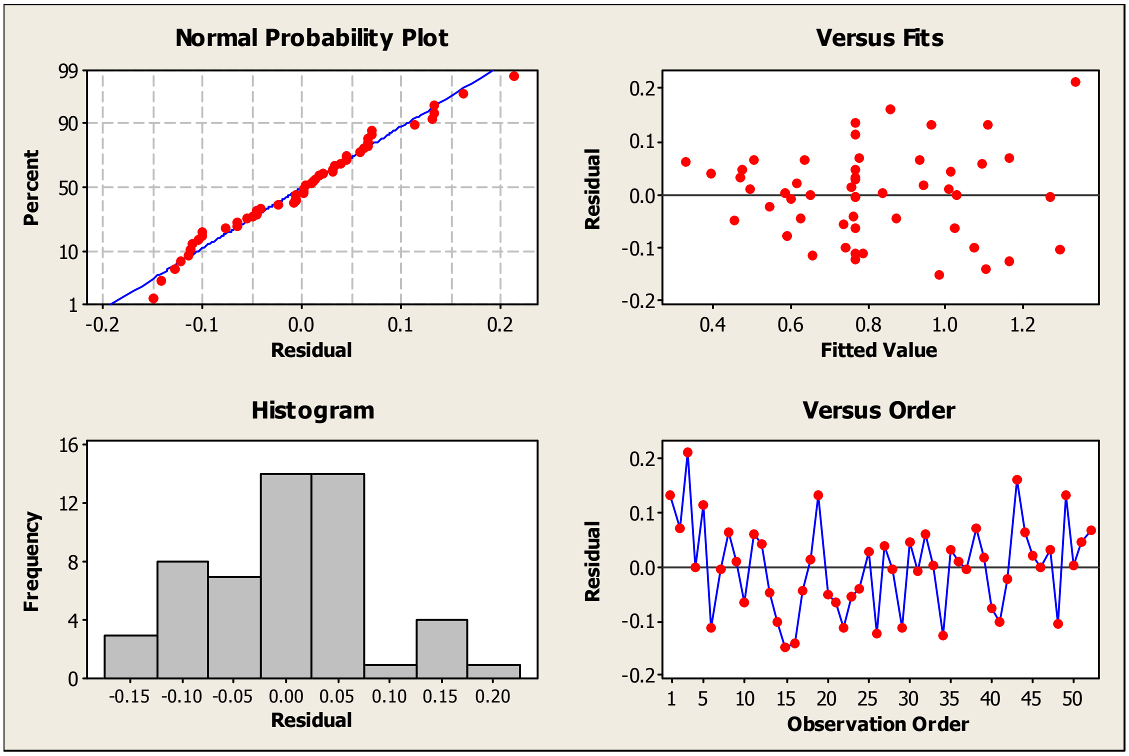

Fig. 2. Residual plots for MRR

Table 2. The ANOVA table for MRR

Source	DF	SS	MS	F	P
Regression	5	2.75200	0.55040	49.70	0.0000
Linear	4	2.69162	0.68199	61.58	0.0000
Ton	**1**	**2.34275**	**0.68199**	**211.56**	**0.0000**
Toff	**1**	**0.31545**	**0.31545**	**28.49**	**0.0000**
IP	1	0.00239	0.00239	0.21	0.6480
WT	**1**	**0.03077**	**0.06857**	**6.19**	**0.0170**
SV	**1**	**0.00265**	**0.06290**	**5.68**	**0.0210**
Ton*Toff	1	0.00048	0.00048	0.04	0.8370
Ton*IP	1	0.00644	0.00644	0.57	0.4550
Ton*WT	1	0.01030	0.01030	0.92	0.3460
Ton*SV	1	0.00058	0.00058	0.05	0.8220
Toff*IP	1	0.00092	0.00092	0.08	0.7760
Toff*WT	1	0.03863	0.03863	3.44	0.0730
Toff*SV	1	0.01484	0.01484	1.32	0.2590
IP*WT	1	0.00197	0.00197	0.18	0.6780
IP*SV	1	0.00800	0.00800	0.71	0.4050
WT*SV	**1**	**0.06038**	**0.06038**	**5.45**	**0.0240**
Ton*Ton	1	0.00456	0.00456	0.41	0.5290
Toff*Toff	1	0.04759	0.04759	1.23	0.8400
IP*IP	1	0.00075	0.00075	0.07	0.7980
WT*WT	1	0.00737	0.00737	0.66	0.4240
SV*SV	1	0.01651	0.01651	1.47	0.2350
Residual Error	46	0.50940	0.01107		
Lack-of-Fit	19	0.27681	0.01457	1.69	0.1030
Pure Error	27	0.23259	0.00861		
Total	51	3.26140			
$F_{0.05,1,46}$=4.02	R^2= 0.9424		R^2adj.=0.9336		R^2pre.=0.9204

It is always necessary to validate the assumptions in the ANOVA using residual plots for normality, random variation, constant variance, and potential outliers. Fig. 2 illustrates an approximately straight line pattern of residuals in normal probability plot and the approximate symmetric nature of histogram signifying normal distribution of residuals. Furthermore, the residuals possess constant variance as they are scattered randomly around zero in residuals versus the fitted values. Since residuals exhibit no clear pattern, there is no error due to time or data collection order. Table 2 illustrates ANOVA for MRR. Accordingly, the investigations have been made for all the parameters. Sequentially, less significant parameters have been eliminated from the model. Conversely, the parameters at 95% confidence level have been included in the model and the empirical model has been developed for MRR and represented by Eq. (3).

$$\begin{aligned}\mathrm{MRR} = {} & -3.9233 + 0.0807 \times \mathrm{Ton} - 0.0296 \times \mathrm{Toff} - 0.0035 \times \mathrm{WT} \\ & -0.1235 \times \mathrm{SV} + 0.0002 \times \mathrm{WT} \times \mathrm{SV} \qquad (3)\end{aligned}$$

Table 2 shows the various statistics obtained through ANOVA. The model F-value of 49.70 implies the model is significant. There is negligible chance that a model F- value of this large could occur due to noise. The P-values of less than 0.0500 indicate model terms are significant at 95% confidence level. In this case Ton, Toff, WT and SV are significant terms of material removal rate at 95% confidence level. The lack of fit P-value of 0.1030 implies the lack of fit is not significant. The lack of fit not significant is desirable.

3.2 Model Analysis

Figs. 3-6 show contour plots of MRR vs significant parameters. It is observed that higher MRR is obtained with higher and lower values of the Ton and Toff respectively. This is due to the fact that the higher value of Ton increases cutting time and transfers more thermal energy from the wire to the workpiece. This will melt and vaporize more material from workpiece resulting higher MRR. Hence for higher MRR, Ton should be set at a maximum possible higher level. However, too high Ton leads to wire breakage.

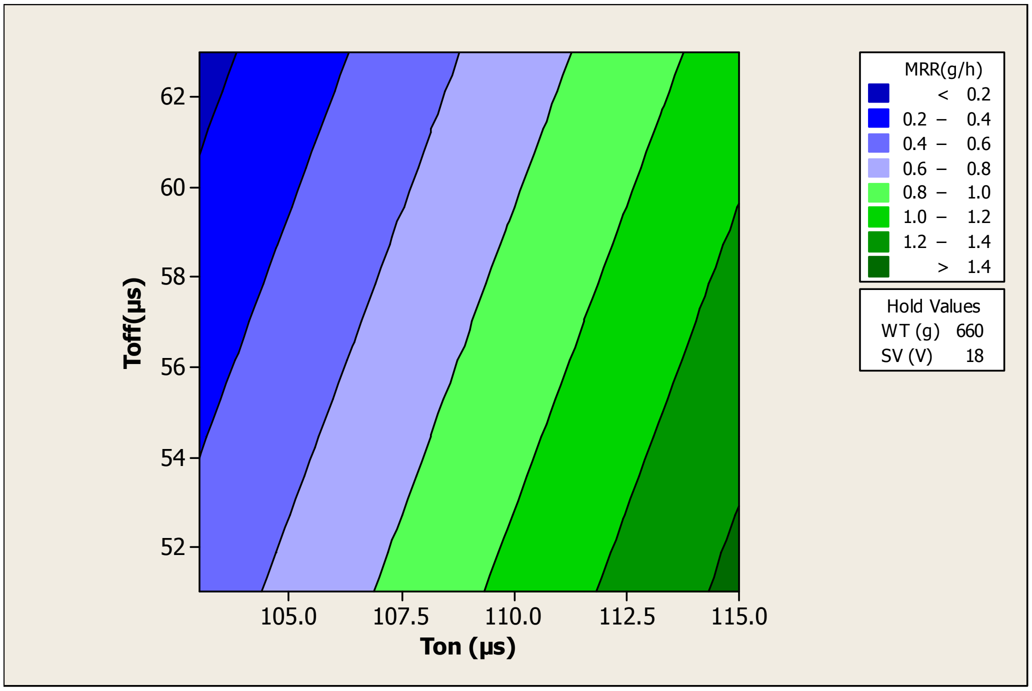

Fig. 3. Contour plot of MRR vs Ton, Toff

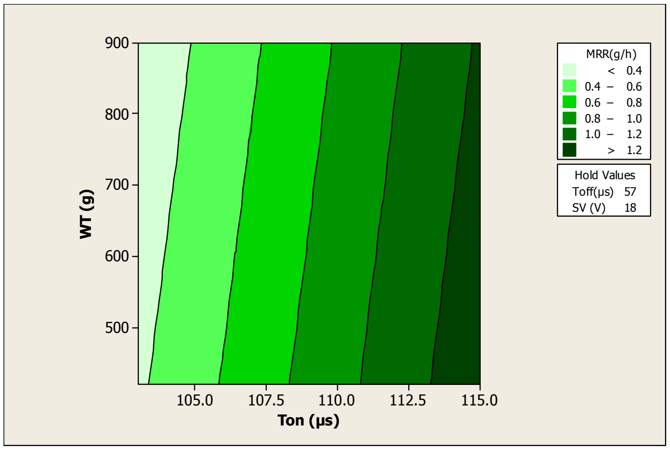

Fig. 4. Contour plot of MRR vs Ton, WT

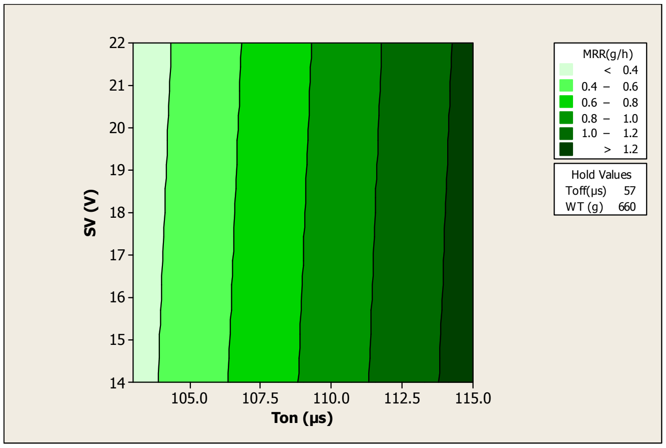

Fig. 5. Contour plot of MRR vs Ton, SV

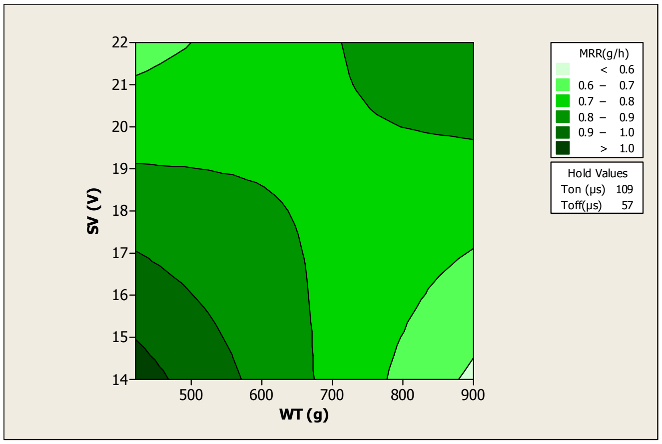

Fig. 6. Contour plot of MRR vs WT, SV

It is seen from Fig. 4 that MRR has decreased trend with increasing WT. With decrease in WT the wire vibration increases, which favours the MRR [8]. However, too low wire tension may cause unstable machining because of variation in the gap between the wire and the workpiece. It is seen from Fig. 4 that at the lower levels of Ton, higher material removal could be obtained by setting WT at the higher levels whereas, at higher levels of Ton, higher MRR could be obtained by setting WT at lower levels. Therefore, an appropriate combination of Ton and WT gives higher MRR. Fig. 5 depicts mild effect of SV on MRR. It is seen that higher MRR can be obtained by setting Ton and SV at higher and lower levels respectively. Similarly, at low levels of Ton, higher MRR could be obtained by setting SV at higher levels. This implies that an appropriate combination of Ton and SV are necessary to obtain higher MRR.

Fig. 6 illustrates the combined effect of WT and SV on MRR. The contour plot has curve lines indicating the interaction between WT and SV. It is observed from Fig. 6 that higher MRR is obtained by setting both WT and SV either at their lower or higher levels. This is because, when SV has been set at lower level, static force acting on the wire may be low and hence lower level of WT serve the purpose. When the SV is set at higher level, the static force acting on the wire may be high which produces the vibrations to the wire [9]. Therefore, for stable machining WT has to be set at higher level. This implies the major role of static force on MRR.

4 Conclusions

The authors studied machinability aspects of WEDMing of W-30Cu MMC for MRR. It was observed that higher values of Ton and lower values of Toff, WT and SV give higher MRR. Ton and Toff have high impact on MRR on contrary, IP, WT and SV have low impact. Moderate wire vibrations favoured MRR. Electrostatic force has a significant role in wire vibrations and hence in MRR. Different empirical models were developed for MRR to correlate the significant machining parameters viz. Ton, Toff, WT and SV. The developed empirical models were compared on the basis of absolute mean predictive error and an adequate model was selected for MRR. The selected model can also predict values for MRR for different input parameter values within the experimental domain.

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