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Experimental investigation of process parameters for conductive graphite abrasive mixed EDM of WC alloy

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Abstract: The aim of current experimental investigation is to perform and study the effect of input processing parameters for abrasive mixed electrical discharge machining (PM-EDM) of tungsten carbide alloy. Mainly, four input processing parameters have been studied, i.e., pulse duration, peak current, abrasive concentration and abrasive grain size for the machinability evaluation of material removal rate and tool wear rate. In this study, graphite (C) abrasive is suspended into the dielectric fluid to make the discharging process stable and uniform, which results in improvement of process mechanism and efficiency. However, this study highlights the mathematical modelling to express the inter relationship between input processing and performance characteristics with the help of response surface methodology (RSM). Results from the study shows the positive influence of graphite abrasive used for PM-EDM of WC alloy with reduction in tool wear rate (5.22%) along with the achievement of significant material removal rate (6.74%).

Keywords: abrasive; graphite; discharge; tungsten; alloy; ANOVA; response surface methodology; RSM; machining; material removal rate; MRR; tool wear rate; TWR.

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1 Introduction

The electrical discharge machining (EDM) process is one of the oldest, popular and a non-traditional machining method (Kumar and Batra, 2012). As this process is popular due to its vast applicability in processing of difficult-to-machine (DTM) hybrid materials (Jahan et al., 2011), but still it has some limitations (Kumar et al., 2010a; Singh and Sharma, 2016, 2017) which are:

1 low removal rate
2 non-acceptable surface finish
3 formation of large micro-cracks and heat affected zones.

To overcome these limitations, researchers are using abrasives such as graphite, silica, silicon carbide, aluminium, etc. to improve the mechanism and achieve improved performance characteristics. The main purpose of using abrasives is to machine these DTM materials efficiently whereas tungsten carbide (WC) is regarded as most DTM and influencing engineering material which has such extreme applications in nowadays competitive global market (Lee and Li, 2001). EDM process has been recognised as the best and economically feasible method to machine WC (Jahan et al., 2011).

In past, Lee and Li (2001) observed the performance of various input parameters for EDM of WC. They showed that high pulse duration and current responsible for high material removal rate (MRR) and surface roughness (SR) of WC. Whereas, Mahdavinejad and Mahdavinejad (2005) studied the machining properties for different grades of WC by using EDM and concluded that there is a problem of instability of process during the machining of WC. Lin et al. (2008) performed the EDM of tungsten carbide by using the pulse-on time, current, duty factor and workpieces as input variables and observed the output responses, MRR, electrode wear ratio (EWR) and SR. Kanagarajan et al. (2008) investigated the four processing parameters: pulse-on time, electrode rotation, current and flushing pressure of EDM were chosen as variables for studying MRR and SR as responses by using central composite design (CCD) method. As per results, pulse-on time and current are the most influencing process parameters which affect machining of WC-Co. Kung et al. (2009) used response surface methodology (RSM) method to optimise the process parameters for WC with PM-EDM process and concluded that Al abrasive mixed in dielectric fluid helps to increase the efficiency of the EDM process. Assarzadeh and Ghoreishi (2013) worked on the multi-objective optimisation of WC-Co by considering current, gap voltage, duty cycle and pulse-on time as the input variables and CCD as methodology. Sharma and Singh (2016) successfully developed a method that optimises the multi-performance characteristics (MPCs), (i.e., micro-hardness and SR) by using Taguchi method with grey relational analysis for the abrasive mixed electric discharge machining process. Authors successfully found the optimal combination of parameters.

Table 1 Literature survey and research gap for abrasive mixed EDM of DTM materials

Sl. no.	*Author/year*	*Abrasives used*	*RSM used*	*Work done*	*Remarks*
1	Wong et al. (1998)	Graphite (38 ± 3 μm) Silicon (45 ± 3 μm) Aluminum (45 ± 3 μm) Crushed glass (2.0 ± 0.07 mm) Silicon carbide (2.36 ± 0.08 mm) Molybdenum sulphide (1–3 μm)	×	This paper presents a study of the near-mirror-finish phenomenon in electrical discharge machining when fine abrasive is introduced into the dielectric fluid. According to authors, the use of negative electrode polarity is necessary to achieve the mirror-finish condition and other features of the PM-EDM process are shorter machining time, more uniform dispersion of the electrical discharges, and stable machining.	• From extensive literature survey, abrasives are found very useful to enhance the process efficiency as they made process stable by improving the surface finish and MRR. • According to authors, Wong et al. (1998), Batish et al. (2012), Singh et al. (2014), Sharma and Singh (2016) and Talla et al. (2016) the graphite abrasive is significantly helpful to enhance the performance characteristics related to EDM process. The recent literature survey shows that graphite abrasive is still under observation of many researchers and hence required further detailed investigation. • In literature, large number of authors studied the silicon abrasive for EDM of DTM materials. But very few authors are found who analysed the effect of graphite abrasive mixed EDM process. • Few authors trying to observe the effect of different concentration and grain size of abrasive respectively.
2	Pecas and Henriques (2003)	Silicon (10 μm)	×	In this work, authors used silicon abrasive mixed dielectric fluid to machine difficult-to-machine material. The results show the positive influence of the silicon abrasive in the reduction of the operating time, required to achieve a specific surface quality, and in the decrease of the surface roughness.	
3	Kansal et al. (2005)	Silicon (20–30 μm)	✓	In this research, silicon abrasive was suspended into the dielectric fluid of EDM and an enhanced rate of MRR and surface finish has been achieved. Authors successfully performed the empirical modeling with the help of response surface methodology.	
4	Kung et al. (2009)	Aluminum (1.5, 2 and 2.5 μm)	✓	In this experimentation, aluminum abrasive has been used to perform PM-EDM of WC. This study was made only for the finishing stages and has been carried out taking into account the four processing parameters: discharge current, pulse on time, grain size, and concentration of aluminum abrasive. The experimental plan adopts the face-centered central composite design (CCD).	
5	Batish et al. (2012)	Graphite and aluminum	×	The present article investigates the PM-EDM of EN31, H11 and high carbon high chromium (HCHCr) die steel materials by using graphite and aluminum abrasive in dielectric fluid. Results shows that graphite abrasive was found to be more suitable compared to aluminum in improving the surface properties..	

Table 1 Literature survey and research gap for abrasive mixed EDM of DTM materials (continued)

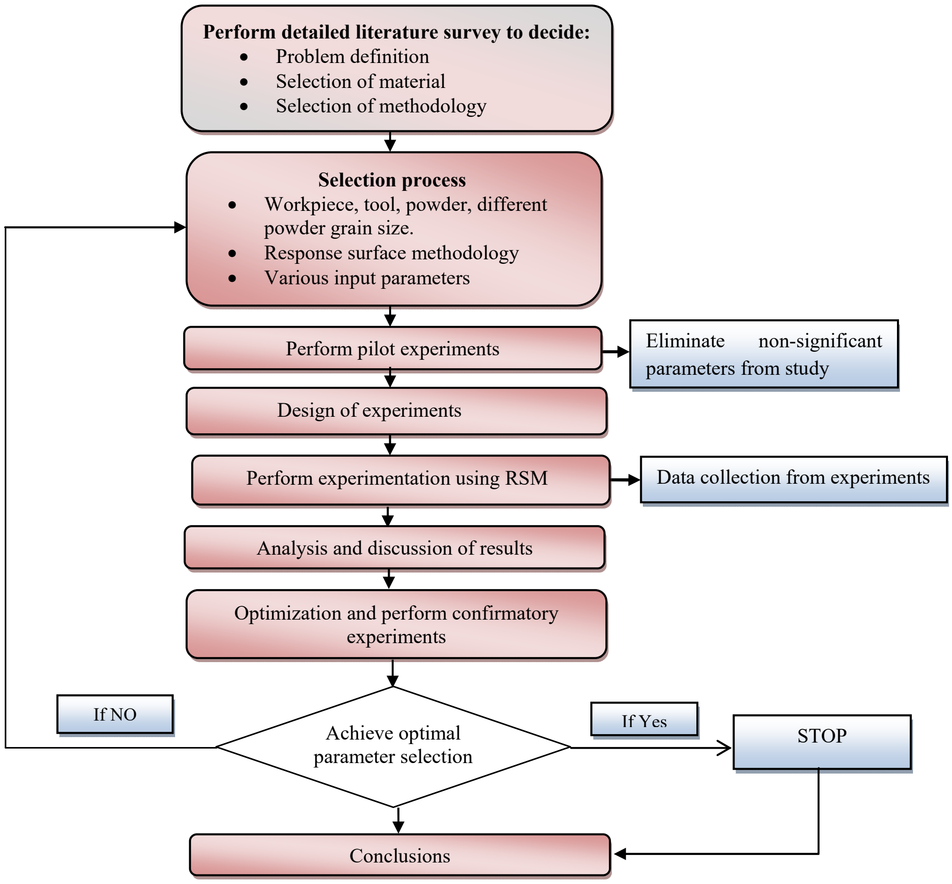
Sl. no.	*Author/year*	*Abrasives used*	*RSM used*	*Work done*	*Remarks*
6	Singh et al. (2014)	Graphite	×	This work has been performed using conductive (graphite) PM-EDM of super Co 605 and optimisation is carried out by means of Taguchi method. The process input parameters selected are flushing pressure, discharge voltage, pulse on-time, polarity, peak current, and pulse off-time. The improvement has been observed in MRR, TWR and SR is 73.98%, 93.56%, and 148.99%, respectively which shows the significance of graphite abrasive.	• RSM has been found effective technique to perform experimentation as it also helps in performing empirical modeling of the process. • Literature survey shows that only authors Kung et al. (2009) performed the PM-EDM of tungsten carbide by using aluminum abrasive particles in dielectric fluid. Sharma and Singh (2016) performed a comparative study between the aluminum and graphite abrasive and found graphite abrasive most effective and significant. The literature survey performed by the authors gives motivation to perform this work. As no author found who used graphite abrasive particles during EDM of WC alloy. Further, no author investigate the in-depth detail of graphite abrasive properties like concentration and grain size for PM-EDM of WC alloy, which is very essential to understand the behavior of these properties upon machining of such s DTM materials. Therefore, this helps to increase the uniqueness of performed work and also enhance some knowledge about the effect of various input parameters upon the abrasive-mixed electrical discharge machining of tungsten carbide for new researchers working in this field.
7	Kolli and Kumar (2015)	Surfactant + graphite	×	In this paper, Taguchi method was employed to optimise the surfactant and graphite abrasive concentration in dielectric fluid for the machining of Ti-6Al-4V using EDM. The process parameters such as discharge current, surfactant concentration and abrasive concentration were observed. It was observed from the experimental results that the graphite abrasive and surfactant added dielectric fluid significantly improved the MRR, reduces the SR, TWR and recast layer thickness at various conditions.	
8	Sharma and Singh (2016)	Graphite and alumina	×	Authors used alumina and graphite abrasive for abrasive mixed EDM of WC alloy by using Taguchi technique. Graphite abrasive founds more useful to optimise the surface roughness and micro-hardness for PM-EDM of WC.	
9	Talla et al. (2016)	Graphite	✓	This work used graphite abrasive and evaluated its role in combination with concentration and machining parameters. Smoother surface with larger craters were realised during abrasive-mixed EDM due to the decrease in discharge energy density.	

Abrasives such as graphite (Gr), silicon (Si) and aluminium (Al) mixed inside the dielectric fluid were seem to produced very high surface finish corresponds to high MRR (Narumiya et al., 1989; Takawashi et al., 1983). Jeswani (1981) used C abrasive in dielectric fluid and shows that MRR should be increased as 60% and tool wear rate (TWR) reduced as 15%. In another study, authors concluded that with addition of Si or Gr abrasive with particle size below 15 µm and a low abrasive concentration (range 2–15 g/l) is enough to get the low SR, i.e., 1.8 and 2.0 µm (Pecas et al., 2001). The literature survey performed on various abrasives used in abrasive-mixed EDM of DTM materials as shown in Table 1. Authors also show the literature gap and motivation to perform this work.

2 Materials and methods

For basic understanding of this study, a framework has been designed and the various steps performed in this study are also shown in Figure 1.

Figure 1 Framework for the PM-EDM of tungsten carbide alloy (see online version for colours)



After performing the literature survey and number of pilot experimentation, the varying and fixed factors with settings/levels were chosen as shown in Table 2 to investigate the efficiency of process in terms of MRR and TWR. The input processing parameters has been considered at three levels, whereas the range for individual parameter is shown in Table 2.

Table 2 Varying and fixed factors with settings/levels

Sl. no.	*Machining parameters*	*Units*	*Symbol*	*Levels*		
				Level-1	*Level-2*	*Level-3*
Varying input parameters						
1	Pulse-on time	µs	A	15	57	100
2	Current	A	B	3	6	9
3	Abrasive concentration	g/l	C	10	15	20
4	Abrasive size	µm	D	45	55	65
Fixed input parameters						
1	Open circuit voltage	V		135 ± 5%		
2	Polarity	(+/–)		Positive		
3	Tool	-		Copper		
4	Machining time	Minutes		10		
5	Powder concentration	g/l		15		

The experimental work has been performed on CNC EDM spark erosion Charmilles Technologies (model no. ROBOFOR M20) as shown in Figure 2. To prevent the mixing of abrasives into the EDM fluid tank, a separate machining tank of 10 L capacity is used. Tungsten carbide alloy (WC) is used as workpiece and electrolytic copper is used as a tool material (details are provided in Table 3), whereas EDM oil is chosen as the dielectric oil. As per literature review, grain size of abrasive have great influence upon the machining efficiency and it needs detail investigation, therefore graphite abrasive with having three different grain sizes; 45 µm, 55 µm and 65 µm have been used. The values of output responses are calculated by using equation (1) for all the performed experiments.

To evaluate the PM-EDM machining performance, the MRR or TWR is estimated after the each run by calculating the initial and the final weight of sample in specified set of conditions as shown in equation (1):

$$\text{MRR or TWR} = \frac{w_i - w_f}{\rho \times t} \times 1000\text{mm}^3 / \text{min} \tag{1}$$

w_i = initial weight, w_f = final weight, t = time period for trials, ρ = density of sample.

MRR and TWR are calculated by weighing measuring machine having least count as 0.001 gm.

In this work, RSM (Montgomery, 2009) is used to investigate the output responses for PM-EDM of WC alloy. Face-centred composite design (FCCD) designs consists the pair of two-level factorial points, the axial point and centre run. The FCCD can be generated using CCD with an axial distance (α = 1). In this work, 30 experiments were performed by maintaining the input parameters at selected levels as given in Table 4. The experimental design contains 16-factorial points, eight-axial on face corresponds to value of α is 1 has six-central points. Further, detailed investigation of experimental results for MRR and TWR is done using analysis of variance and regression modelling respectively.

Table 3 Specification and properties of workpiece (WC alloy) and tool (Cu)

Sr. no.	*Properties*	*Details*	*Properties*	*Details*
	Workpiece		*Tool*	
1	Material	Tungsten carbide	Material	Electrolytic copper
2	Chemical composition	W-65.50%, Ti-15.47%, Co-10.07%, Nb-4.69% and Cu-3.66%	Composition	99.9% copper
3	Size of the workpiece	90 mm × 60 × 10 mm	Density	8.914 g/cm^3
4	Density	15.1 g/cm^3	Melting point	1,083ºC
5	Hardness	1,800 HVN	Electrical resistivity	9 μΩcm
6	Melting point	2,597ºC	Hardness	HB 100
7	Tensile strength	179 Kg/mm^2	Diameter used	17 mm
8	Compressive strength	410 Kg/mm^2	-	-
9	Toughness	50 Kg/mm^2	-	-

Figure 2 Experimental setup of abrasive-mixed EDM machine (see online version for colours)

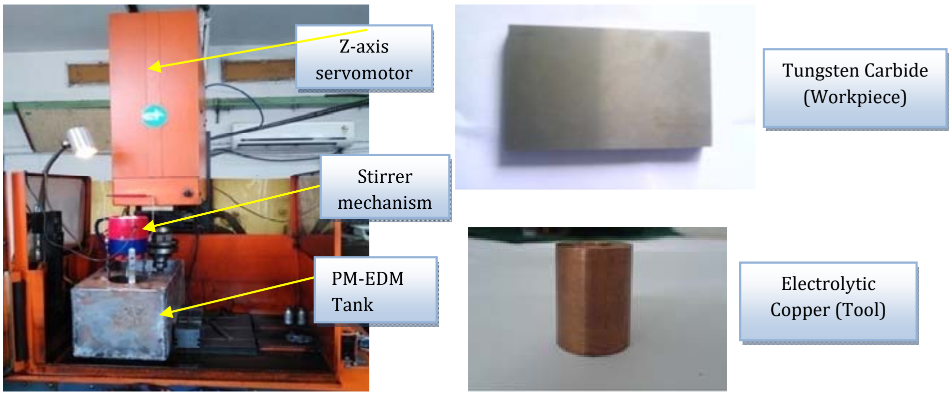


Table 4 Experiments performed with RSM technique

Sr. no.	*Pulse-on time, µs*	*Current, amp*	*Abrasive conc., g/l*	*Abrasive size, µm*	*MRR (mm^3/min)*	*TWR (mm^3/min)*
1	57.00	6.00	15.00	55.00	4.940	1.688
2	57.00	6.00	15.00	55.00	5.612	1.435
3	100.00	9.00	10.00	45.00	6.221	1.308
4	57.00	6.00	10.00	55.00	4.196	1.667

Table 4 Experiments performed with RSM technique (continued)

Sr. no.	*Pulse-on time, µs*	*Current, amp*	*Abrasive conc., g/l*	*Abrasive size, µm*	*MRR (mm^3/min)*	*TWR (mm^3/min)*
5	57.00	9.00	15.00	55.00	7.723	1.119
6	57.00	6.00	15.00	55.00	5.893	1.503
7	57.00	6.00	15.00	55.00	4.869	1.442
8	100.00	3.00	10.00	65.00	4.624	1.874
9	15.00	3.00	20.00	65.00	3.467	1.878
10	57.00	6.00	15.00	45.00	5.348	1.542
11	100.00	9.00	20.00	45.00	6.290	1.692
12	15.00	3.00	10.00	45.00	3.240	1.656
13	100.00	6.00	20.00	65.00	5.571	2.184
14	57.00	6.00	15.00	55.00	5.393	1.265
15	100.00	9.00	15.00	55.00	5.623	0.976
16	57.00	3.00	15.00	55.00	4.984	1.452
17	15.00	9.00	10.00	65.00	4.458	1.861
18	100.00	3.00	10.00	45.00	4.384	1.466
19	100.00	3.00	20.00	45.00	4.167	1.778
20	15.00	6.00	15.00	55.00	5.693	0.988
21	57.00	6.00	20.00	55.00	4.651	1.594
22	100.00	3.00	20.00	65.00	4.820	2.448
23	15.00	3.00	20.00	45.00	3.266	1.966
24	57.00	6.00	15.00	55.00	6.143	1.209
25	15.00	3.00	10.00	65.00	4.184	1.398
26	15.00	9.00	10.00	45.00	5.620	1.669
27	57.00	6.00	15.00	65.00	3.477	1.432
28	15.00	9.00	20.00	45.00	4.452	1.741
29	15.00	9.00	20.00	65.00	4.380	2.006
30	100.00	9.00	10.00	65.00	4.161	2.228

3 Analysis of variance for response characteristics

The FCCD is used to perform the 30 experiments by using selected input parameters. Further, analysis of experimental results is performed by using ANOVA analysis and regression modelling. The results are discussed in detail for both of the response characteristics, i.e., MRR and TWR followed by perturbation plot analysis for both the response characteristics.

To investigate the data, i.e., to check the goodness for fitness of model is required. Analysis includes regression analysis, test of lack of fit, the test of significance of model and percentage of contribution during adequate checking of model (Montgomery, 2009). To perform this detailed investigation, analysis of variance is used. ANOVA is performed for both the response characteristics, MRR and TWR.

3.1 Analysis of variance for MRR

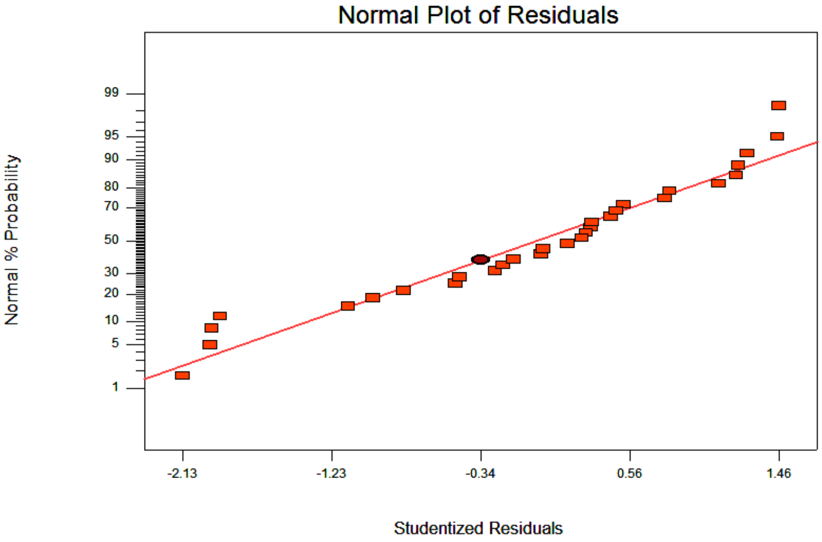
Summary of results for MRR suggested that model has 39.29 F-value which indicates that this model is statistically significant as shown in Table 5. Further, ANOVA shows that R-squared and adjusted R-squared for MRR is 80.57% and 77.96%. Hence, the regression modelling shows the admirable justification of good relationship between the response (MRR) and various input parameters whereas, the R-squared value explains the variation happened in model in the percentage form corresponds to total variability in actual data. According to Singh et al. (2015), if the R-squared value approaches towards unity (100%), this shows the good explanation of investigated data of model. In this study, R^2 predicted (72.84) shows the good conformity with the R^2 adjusted (77.96). The related *p*-value of model is below 0.05 ($\alpha = 0.05$) at 95% confidence level shows that model is considered as significant (Montgomery, 2009), whereas lack-of-fit is in-significant in study, as it desired. To fit the quadratic model suitably for MRR, the in-significant factors are getting removed using backward elimination method, whereas the contributing factors of this study is shown in Table 5.

Table 5 Analysis of variance for MRR-reduced quadratic model

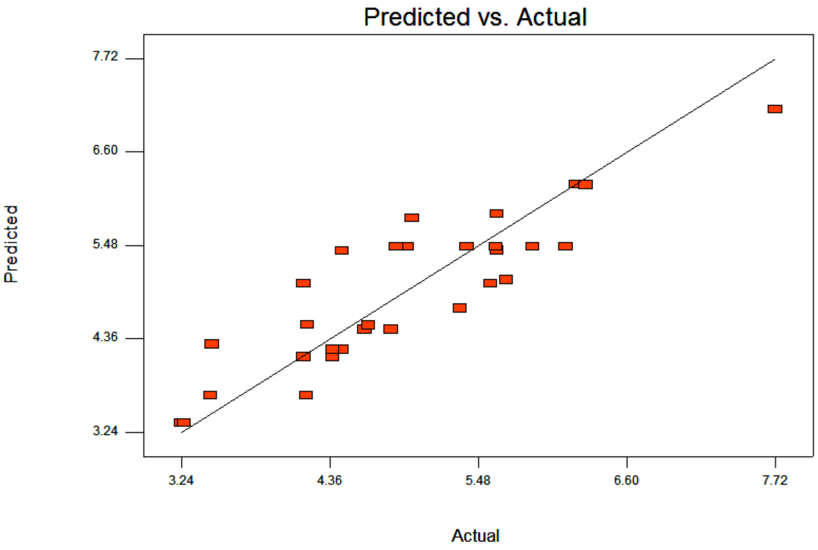
Source	*Sum of squares*	*DF*	*Mean square*	*F-value*	*Prob. > F*	*% contribution*
Model	23.36	8	2.92	39.29	< 0.0001	
A	4.81	1	4.81	12.93	< 0.0001	16.05
B	7.68	1	7.68	24.44	< 0.0005	25.63
B^2	2.79	1	2.79	8.89	0.0071	9.31
C^2	2.50	1	2.50	7.94	0.0013	8.34
D^2	2.12	1	2.12	7.18	0.0133	7.07
BD	5.30	1	5.30	10.08	0.0093	17.69
Residual	3.60	21	0.18			12.02
Lack of fit	5.30	16	0.33	1.27	0.4266	
Pure error	1.30	5	0.26			4.34
Cor total	29.96	29				
Std. dev.		0.56		R-squared	80.57	
Mean		4.92		Adj R-squared	77.96	
Coefficient of variation		15.31%		Pred R-squared	72.84	

The percentage contribution for each term has been calculated by the sum of squares of that particular term and to total sum of square. In this study, current (B) shows the highest contribution for MRR, i.e., 25.63% followed by pulse-on time (A) 16.05%, interaction of current (B) with abrasive grain size (D) 17.69%, the quadratic effect of factor peak current (B^2), the quadratic effect of factor abrasive concentration (C^2), the quadratic effect of factor abrasive grain size (D^2). From Table 5, it has been observed that coefficient of variation for MRR is 15.31%, which shows the excellent accuracy of the results. Figure 3(a) displays the normal probability plot of residuals for MRR. Notice that the residuals are falling on the straight line, which shows that errors are distributed normally.

Figure 3 (a) Normal probability plot residuals for MRR (b) Plot of actual vs. predicted response of MRR (see online version for colours)



(a)



(b)

Further, each observed value when compared with predicted value as shown in model shown in Figure 3(b). It can be observed from respective Figure 3 that the regression model is fairly fitted with the analysed values. After the elimination of non-significant terms, the response equation for MRR is as follows:

- (In coded terms)

$$\begin{aligned} \text{MRR} &= 5.46 + 0.39 \times \text{A} + 0.65 \times \text{B} - 1.111\ \text{E} - 003 \times \text{C} - 0.21 \\ &\quad \times \text{D} + 0.99 \times \text{B}^2 - 0.94 \times \text{C}^2 - 0.95 \times \text{D}^2 + 0.42 \times \text{B} \times \text{D} \end{aligned} \tag{2}$$

- (In actual factors)

$$\begin{aligned} \text{MRR} &= -32.66357 + 9.2941 \times 10^{-3} \times \text{Pulse-on} - 0.41057 \times \text{Current} \\ &\quad + 1.12532\ \times \text{Abrasive Conc.} + 1.10261 \times \text{Abrasive Size} + 0.11023 \\ &\quad \times \text{Current}^2 - 0.037518 \times \text{Abrasive Conc.}^2\ - 9.5295 \times 10 - 3 \\ &\quad \times \text{ Abrasive Size}^2 + 0.212625 \times \text{Current} \times \text{Abrasive Size} \end{aligned} \tag{3}$$

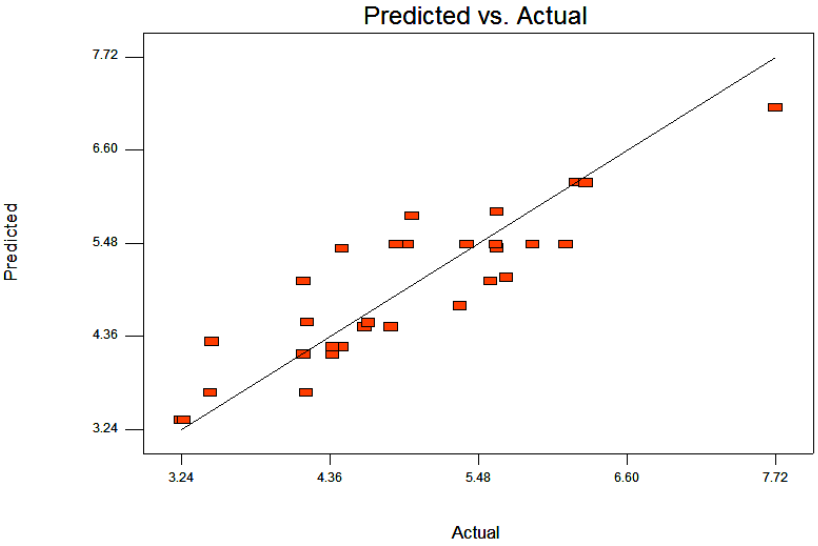
3.2 Analysis of variance for TWR

The fit summary of TWR, i.e., F-value of model is 42.44 suggested that this quadratic model is considered as statistically significant. The ANOVA table (as presented in Table 6) for TWR shows that the R-squared and adjusted R-squared values are 84.62% and 80.61%, respectively. It represents that regression analysis provides the admirable explanation of relationship between input factors and output characteristic, TWR. The value of predicted R^2 (74.32) shows good conformity with the adj. R^2 (80.61). The related p-value of model is below 0.05, $\alpha = 0.05$, at 95% confidence level shows that model is considered as significant (Montgomery, 2009) and lack-of-fit found in-significant for TWR. As the coefficient of variation is observed as 5.79%, this shows the excellent accuracy of the results. With the help of F-test in ANOVA, it is found that factors pulse-on time, A current B, abrasive grain size, D, quadratic term of abrasive concentration, (C^2) interaction effect of pulse duration, A with current B, have significant influence upon the study.

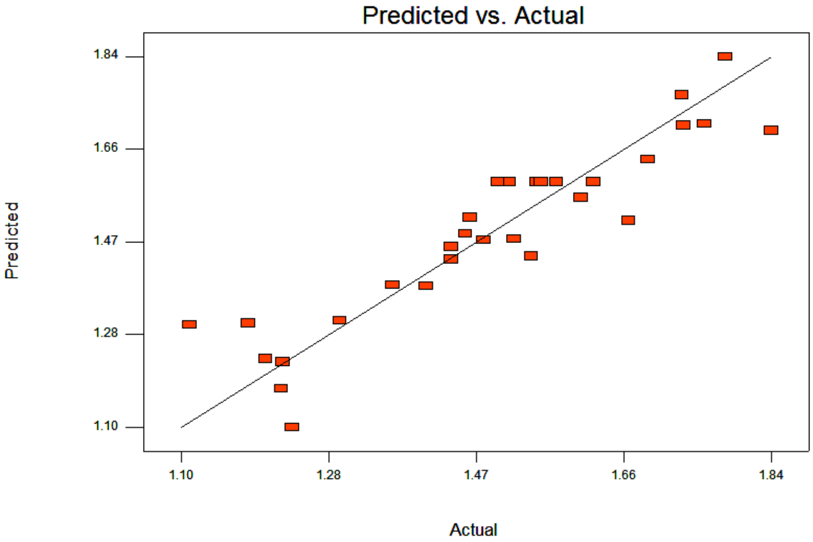
Table 6 Analysis of variance for TWR-reduced quadratic model

Source	*Sum of squares*	*DF*	*Mean square*	*F-value*	*Prob. > F*	*% contribution*
Model	0.94	6	0.16	42.44	< 0.0001	
A	0.36	1	0.36	33.12	< 0.0001	25.89
B	0.28	1	0.28	31.44	< 0.0001	20.14
D	0.19	1	0.19	25.88	< 0.0001	13.66
C^2	0.22	1	0.22	27.52	< 0.0001	15.82
AB	0.037		0.037	4.98	0.0356	2.66
Residual	0.25	23	0.013			17.98
Lack of fit	0.31	18	0.017			
Pure error	0.043	5	8.654E-003			3.09
Cor total	1.39	29				
Std. dev.		0.086		R-squared	84.62	
Mean		1.49		Adj R-squared	80.61	
Coefficient of variation		5.79%		Pred R-squared	74.32	

Figure 4 (a) Normal residual plot for TWR (b) The actual and predicted plot for response TWR (see online version for colours)



(a)



(b)

The percentage of contribution for the significant terms of model is also shown in Table 5; pulse-on time (A) shows high percentage of contribution, i.e., 25.89% for TWR followed by current (B) 20.14%, quadratic term of abrasive concentration (C^2) 15.82%, abrasive grain size (D^2) 13.66% and at least interaction of pulse duration (A) and current (B) 2.66% respectively. Figure 4(a) represents the normal plot residuals of TWR and it shows that observed residuals are falling upon the straight line; this shows that errors are normally distributed. Further, the each experimental value is compared and observed with predicted value as shown in Figure 4(b). It can be observed from Figure 5 that regression model is fitted fairly well with analysed values.

After eliminating the non-significant terms by using backward elimination process, the final response equation for TWR is given as follows:

- (In coded terms)

$$\begin{aligned} \mathrm{TWR} &= 1.59 + 0.15 \times \mathrm{A} + 0.12 \times \mathrm{B} - 0.039 \\ &\quad \times \mathrm{C} + 0.10 \times \mathrm{D} + 0.17 \times \mathrm{C}^2 + 0.048 \times \mathrm{A} \times \mathrm{B} \end{aligned} \tag{4}$$

- (In actual factors)

$$\begin{aligned} \mathrm{TWR} &= -0.63453 + 4.8692 \times 10^{-4} \times \text{Pulse-on} + 0.016278 \\ &\quad \times \text{Current} + 0.19453 \times \text{Abrasive Conc.} + 0.010339 \times \text{Abrasive Size} \\ &\quad + 6.7422 \times 10^{-3} \times \textit{A}\text{brasive Conc.}^2 + 3.7745 \times 10^{-4} \times \text{Pulse-on} \times \text{Current} \end{aligned} \tag{5}$$

4 Result and discussion for response characteristics

The result and discussion for both the response characteristics MRR and TWR is mentioned below.

4.1 Result and discussion for MRR

As tungsten carbide is a very DTM material therefore high input discharge energies are required to remove the material out from the workpiece and abrasives are also added to improve the process mechanism. Result obtained successfully shows the trend for the MRR, it shows that the addition of graphite abrasive helps to improve the machining efficiency by increasing the MMR with respect to high input discharge energies. It is also noticed that the addition of abrasive particle (graphite) helps to make the machining process more stable and capable.

Figure 5 presents the predicted surface response of MRR with respect to input factors current and abrasive size. As it can be observed from Figure 4, MRR shows increasing trend with considerable increase in values of current corresponding to the values of abrasive size. Therefore, high MRR is observed at peak values of current (9A) and medium abrasive size (55 µm). High current gives high removal rate because of high input energy, as per some previous researches (Kung et al., 2009) it was observed that with increase in current the intensity of spark get high that further makes the pulsation energy dominant with high melting rate of workpiece sample which ultimately contributes to high MMR (Singh et al., 2014). Whereas the medium grain size gives high MRR corresponding to the values of current. Results revealed that with further increment in size of abrasive from 55 µm deteriorates the MRR because it results in low electrical density and having high probability of irregular discharge therefore then machining efficiency apparently deteriorated. So to prevent the combined effects of lower electrical power density, non-uniform particle distribution, few particle striking rate and bad discharge transitivity, there is a need of proper addition of abrasive particles in dielectric oil.

Figure 5 Response plot of abrasive grain size and current on MRR (see online version for colours)

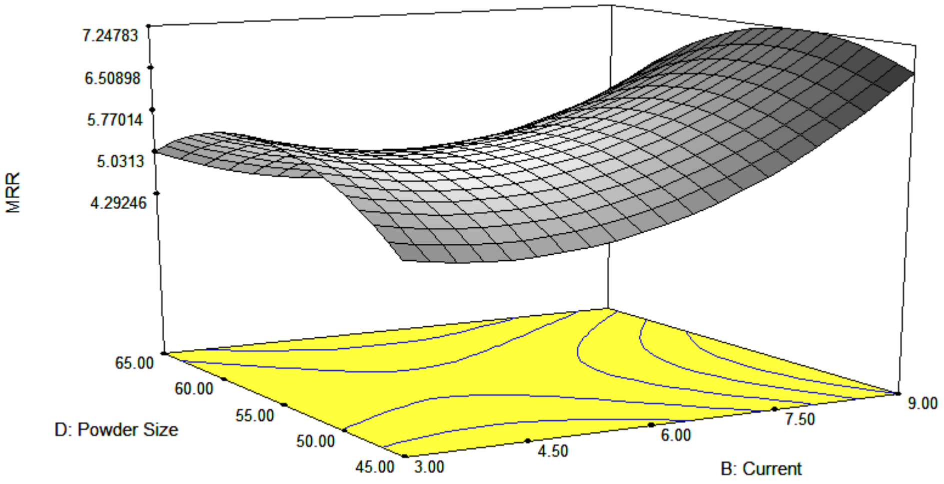
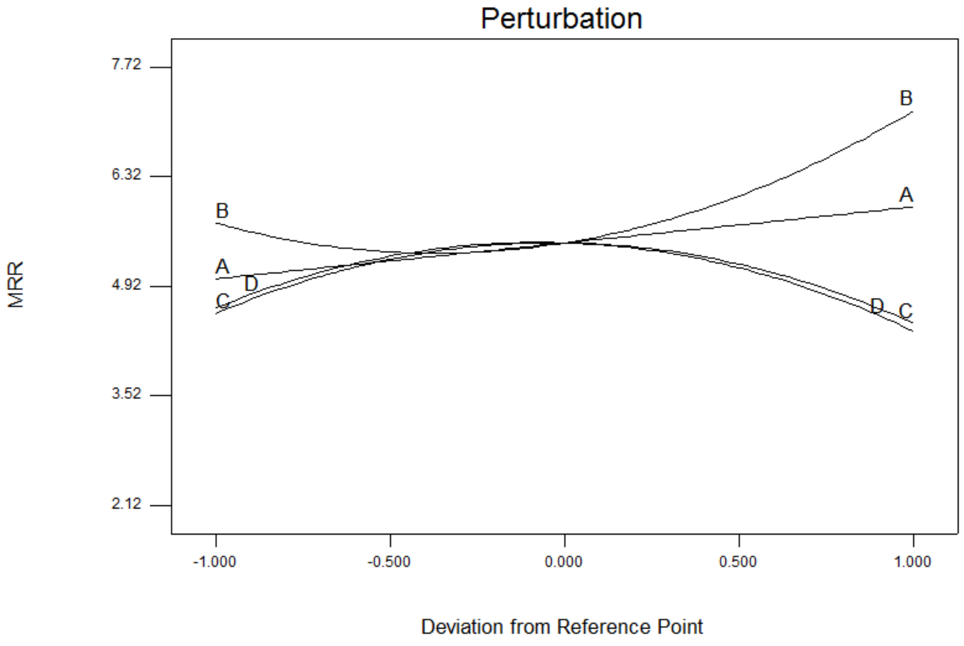


Figure 6 Perturbation response plot presentation for MRR



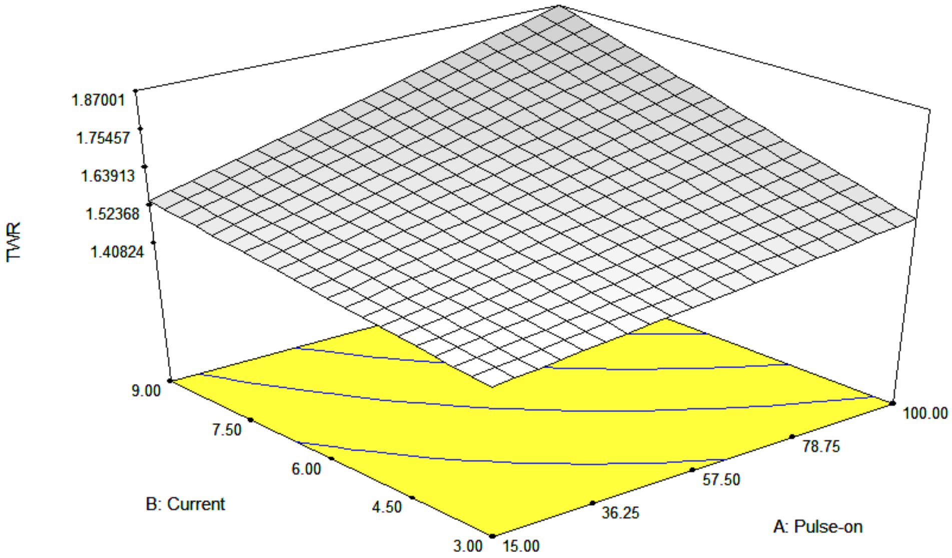
In perturbation plot of MRR as shown in Figure 6, it shows that rise in MRR value due to increase in pulse duration value (15 µs to 100 µs) and current (3A to 9A) due to high input discharge energies, whereas in case of current initially MRR reduces and then abruptly in incremental form. This happens because at high current and pulse-on time more negative ions strike the workpiece surface and mixing of abrasive particles also helps to uniformly distribute that discharge over the desired surface of workpiece. It can be seen from Figure 6 that high concentration of graphite abrasive reduces the MRR and shows the discharge inference phenomenon. At high concentration of abrasive particles, due to high heating effect between the electrodes more debris were generated which further reduces the performance of abrasive particles and eventually stop the sparking stability enhancing process.

This study revealed that with augmentation in graphite abrasive grain size, there is an improvement in MRR but then at higher grain size MRR reduces. It can be explained by both the instability of sparking and larger spark gap by large grain sizes apparently responsible for the deterioration of MRR.

4.2 Result and discussion for TWR

During the powder-mixed EDM of tungsten carbide alloy it was observed that the TWR increases at high input discharge energies due to high removal of material out from the workpiece due to impingement of positive ions towards the tool. Maximum TWR is noticed at high pulse-on time and current values. Figure 7 presents the estimated interaction effect response for TWR relative to input parameters, i.e., pulse duration and current. It shows that TWR gradually enhances due to increase in pulse duration corresponding to each value of current. Due to high discharging of spark with uniform current intensity causes the high TWR. But, still it does not increases abruptly because of graphite abrasive particles between workpiece and tool which stabilises the sparking phenomena and rectify non-uniform discharging, as also shown by Jeswani (1981) and Narumiya et al. (1989). The addition of proper grain size and concentration of abrasive particles are required as the optimal value of both makes the process more stable and improves the process efficiency.

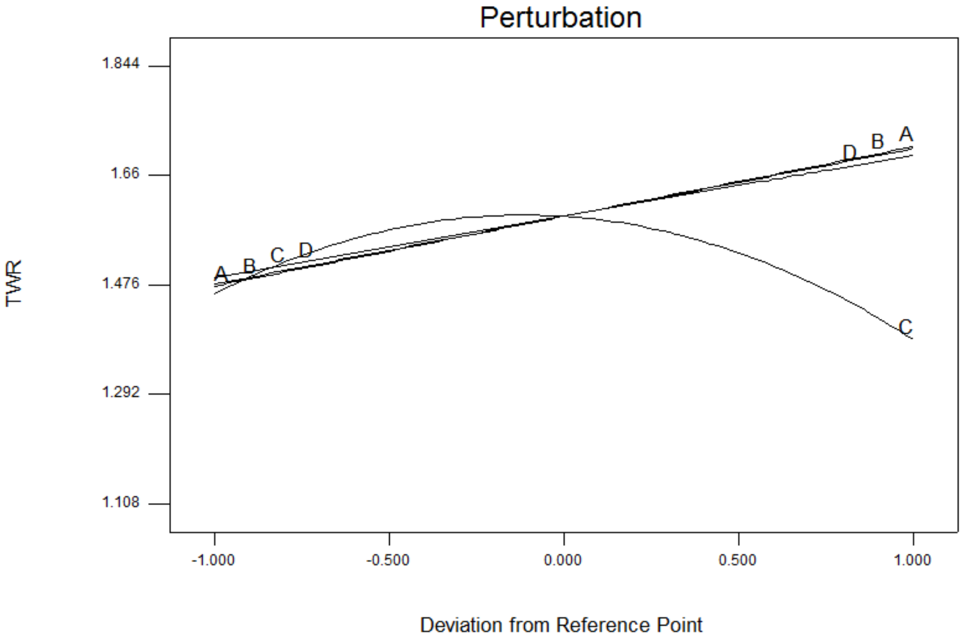
Figure 7 Response plot of pulse duration and current on TWR (see online version for colours)



According to Figure 8, TWR increases due to increase in current (3A to 9A) and pulse duration (15 μs to 100 μs) and due to dominant behaviour of input discharge energies which can melt and vaporises huge amount of material from both the electrodes and these results are in line with previously published work (5, 6). TWR increases with increase in input discharge energy but the mixed abrasive (C) particles inside the dielectric fluid helps to make the process stable (uniformly distributing the discharge) and control the high TWR.

Results show that with increase in concentration of graphite abrasive, initially TWR increases but with further addition of abrasive after (15 gm/l) it shows drastically low values of TWR. As the graphite abrasive particles present in large quantity between the gaps which hinders the proper discharging between the electrodes, this leads to low MMR from both the electrodes. Result shows that graphite abrasive particles help to increase the process efficiency for PM-EDM of WC alloy.

Figure 8 Perturbation response plot presentation for TWR



5 Optimisation and confirmation of results

The optimised values of MRR and TWR have been selected along with optimal input parameter setting as shown in Table 7. During the comparison of best values of MRR from experiment and experimental values at optimised level, considerable improvement has been noticed, i.e., 6.74% for MRR and 5.22% for TWR has been observed.

Table 7 Experimental values at optimised setting

Sl. no.	*Responses*	*Optimised process settings*			
		Pulse-on time	*Current*	*Abrasive concentration*	*Abrasive size*
1	MRR	100	9.00	14.44	52.60
2	TWR	100	5.72	14.36	50.58
		Optimal predicted values	*Confirmatory experiments*	*Best values*	*Improvement in %*
1	MRR	7.697	8.241	7.720	6.74
2	TWR	1.113	0.925	0.976	5.22

6 Conclusions

This work mainly investigates and statistically model the performance characteristics for EDM of WC alloy. The presence of graphite abrasive helps to enhances spark gap which gives us uniform distribution of spark energy and arises the MRR values, whereas reduces the TWR. The model F-value 39.29 for MRR and 42.44 for TWR shows that models for both the responses are statistically significant. The coefficients of variation for both the models are 15.31 and 5.79 respectively, which shows the accuracy of result. An ANOVA result concludes that most influential factor is current for MRR whereas pulse duration is the most influential parameter for TWR. As per results, high input discharge energies, (i.e., high pulse-on time and current) are the major factors which are responsible for high MRR but along with they also cause high TWR. But the addition of graphite abrasive particles controls the high TWR to some extent which further need a detailed investigation. The optimal parameter selection shows 6.74% improvement for MRR and 5.22% for TWR, which is a considerable improvement in performance characteristics by using optimal parameter for the PM-EDM of WC alloy.

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