

# Tool wear rate optimization in PMEDM using titanium powder by Taguchi method for die steels

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(Manuscript Received on March 08th, 2016, Manuscript Revised May 04th, 2016)

## ABSTRACT

*Powder mixed electrical discharge machining (PMEDM) is a complex machining process which is controlled by a number of machining parameters. Each machining parameter has its own influence on performance of the process. For achieving the best performance of the electrical discharge machining (EDM) process, it is crucial to carry out parametric design responses such as Metal Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness(SR). The objective of this paper is to optimization of input parameters for the TWR in PMEDM using powder titanium are presented. The Taguchi*

*method was applied to the processing parameters to investigate the following: workpiece material, tool material, polarity, pulse-on time, current, pulse-off time, and powder concentration. The analysis used the Taguchi method and given the optimal value for TWR with respective parameters. Electrode material affected the strongest factor, the Taguchi coefficient, S/N of TWR. And the optimal value of TWR was 3.092 mm<sup>3</sup>/min. Results from optimization calculations and experimentation have demonstrated high accuracy and efficiency.*

**Keywords:** EDM, PMEDM, TWR, Taguchi method, S/N ratio.

## 1. INTRODUCTION

Electric discharge machining (EDM) is one of the most popular machining methods to manufacture dies and press tools because of its capability to produce complicated shapes and machine very hard materials. But the low machining efficiency and poor surface quality are the major drawbacks of this process which

restricts its use in mechanical manufacturing. To overcome these drawbacks and to enhance process capabilities researchers did a lot of works, as rotating of electrode, orbiting of electrode, application of ultrasonic vibrations and addition of powders in dielectric fluid of EDM,...

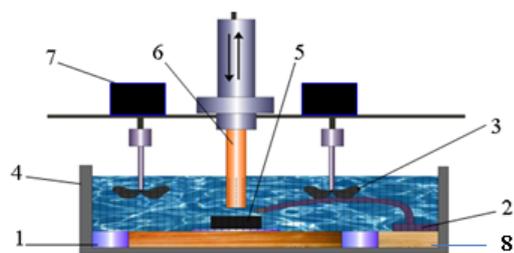
Past research into powder mixed electric discharge machining (PMEDM) methods have proven promising as methods to improve both the productivity and quality in electric discharge machining (EDM). A suitable powder is mixed into the dielectric fluid used in EDM, which can lead to both an increased MRR and TWR. In addition, SR can be reduced and the micro-hardness (HV) of the surface machining can be greatly increased. The Productivity and quality of surface machining of EDM can be increased with Al powder mixed into the dielectric fluid [1,2]. Taguchi method has been widely used to optimize quality characteristics in the field of EDM [3]. The Gr powder helped to increase the MRR, while SiC powder helped to reduce the TWR [4]. The results showed that using powder reduces the TWR. Conversely, an increase in current and pulse on time increased the TWR. Taguchi's method was used to evaluate the level of influence of aluminum powder on SR during machining of a H13 workpiece [5]. Negative electrode polarity and Al powder mixed into the dielectric fluid helped to reduce SR. An optimal value of MRR was determined by Taguchi's method [6]. Powder mixed in the dielectric fluid led to an increased MRR and the maximum value of the MRR obtained was  $12.47 \text{ mm}^3/\text{min}$  with powder concentrations of  $6 \text{ g/l}$ . During the machining of EN31 steel using a PMEDM process, MRR and SR were optimized [7]. The results showed that the MRR and SR were strongly influenced by the concentration of powder and the intensity of electrical discharge. The PMEDM process efficiency was better than that of the EDM process [8]. This contributed to the effectiveness of the PMEDM method. Three different powder materials were used, namely Gr powder, SiC, and  $\text{Al}_2\text{O}_3$ , in the dielectric media. The Gr powder helped to increase the MRR,

while SiC powder helped to reduce the TWR [9]. By using SiC powder, the productivity of the EDM process improved significantly during the machining of WC [10]. The MRR was increased by 90% in comparison to the EDM process. The TWR and SR were reduced when mixed powder was added to the dielectric fluid [11].

From the available literature, it was concluded that the few researchers investigated the effect of powder particles mixed in dielectric fluid by taking electrical parameters as process input parameters. But no work is reported on the influence of process input parameters during PMEDM using powder titanium of die steels. The intent of the present study is to study the effect of different input parameters, namely, current, workpiece material, electrode material, electrode polarity, pulse on time, pulse off time and powder concentration and some their interactions on TWR. The effects of various input parameters on output responses have been analyzed using Analysis of Variance (ANOVA). Main effect plot and interaction plot for significant factors and S/N ratio have been used to determine the optimal design for each output response.

## 2. Experimental procedure

### 2.1 Experimental Equipment



1- Magnets 2- Pump 3- Nozzle  
4- Machining tank 5-Workpiece 6- electrode  
7- Stirring 8-Nonmagnetic material

Figure 1. Schematic line diagram

An electrical discharge machine, AG40L (Sodick, Inc. USA), was used. A schematic experiment is shown in Figure 1. The tank was made of CT3 steel with size 330x180x320 mm and motor shafts were fitted by stirring at 100 rev/min with titanium powder were mixed into the dielectric fluid (oil HD-1) during the experiment (see also Figure 1). The workpiece materials included SKD61, SKD11, and SKT4 mould steel, where the common type used in industry standards were selected for this study. Samples measured 45x27x10mm. Furthermore, Cu, Gr are among the two materials most commonly used, and have been a focus of recent research. The electrode was shaped into a circular cylinder and it had a diameter measuring 23 mm. The size of the particle of titanium powder measuring 45µm were selected and mixed into the dielectric fluid.

The TWR was calculated by measuring the weight of tool electrode after each machining period. The mass before and after processing was measured with an electronic scale AJ 203 (Shinko Denshi Co. LTD - Japan), where the largest mass measured 200 g, with an accuracy of 0.001 g.

## 2.2 Experimental Methods

### 2.2.1 Taguchi Method

The Taguchi method is used to design experiments based on orthogonal matrix, specific to Taguchi, and is used to assess the process parameters. The experimental parameters could receive more than two levels, including a communication between the different possibilities that exist in an experimental design. The experimental design of Taguchi method was implemented by the orthogonal matrix (table) for placement of the process parameters, which were

examined by their levels with the smallest number of experiments during the time as well as the least expensive. The selection of tables was based on the number of parameters and their change rates. ANOVA was based on data obtained from Taguchi's experimental design and was used to select new parameter values to optimize the quality characteristics. To analyze the results of experiments Taguchi used a coefficient, S/N, to evaluate the impact of interference. The ratio, S/N, has a greater value for input parameters and was minimally impacted by noise. In experimental studies, the valuation ratio, S/N, was the highest possible for the results. The Optimal regime of the process parameters was determined by the characteristics of the coefficient S/N [12].

- The *higher- the- better*:

$$(S/N)_{HB} = -10\log\left(\frac{1}{r} \sum_{i=1}^r \left(\frac{1}{y_i^2}\right)\right) \quad (1)$$

Where, r represents some the number of repetitions, and  $y_i$  is the value of experiment results.

- The *Normal - the best*:

$$(S/N)_{NB} = -10\log\left(\frac{1}{r} \sum_{i=1}^r (y_i - y_0)^2\right) \quad (2)$$

Where,  $y_0$  represents the standard values or target values.

- The *Lower- the- better*:

$$(S/N)_{LB} = -10\log\left(\frac{1}{r} \sum_{i=1}^r y_i^2\right) \quad (3)$$

Where,  $y_i$  is the overall typical value of each experiment.

### 2.2.2 Selection of factors and interaction

In the current study, the interaction effects of the input parameters were considered, as shown in Table 1. In the field of PMEDM, researchers have studied the effect of powder size, workpiece material, electrode material,

current, pulse-on time, and pulse-off time. In this study, the interaction terms were considered, specifically workpiece material, x-electrode material (AXB), workpiece material, x-powder concentration (AxG), and electrode material x-powder concentration (BxG).

**Table 1.** Input parameters and its levels

No	Factors	Symbols	Levels			DOF
			Level 1	Level 2	Level 3	
1	Workpiece material	A	SKD61	SKD11	SKT4	2
2	Electrode material	B	Cu	Cu*	Gr	1
3	Polarity	C	-	+	-*	1
4	Pulse-on time ( $\mu$ s)	D	5	10	20	2
5	Current (A)	E	8	4	6	2
6	Pulse-off time ( $\mu$ s)	F	38	57	85	2
7	Powder concentration Ti (g/l)	G	0	10	20	2
8	Interaction of workpiece material and tool material	AxB	-	-	-	2
9	Interaction of workpiece material and powder concentration	AxG	-	-	-	4
10	Interaction of tool material and powder concentration	BxG	-	-	-	2
11	Total					20

\*- *Dummy treated*

### 2.2.3 Selection of Orthogonal array and parameter assignment

Taguchi's orthogonal array's was used for designing the experiments. There are many orthogonal array's available in the Taguchi's method, therefore selection depended upon the number of factors and degrees of freedom of each factor. In this study, seven main factors were considered, out of which, two factors were at two levels, each having one degree of freedom. Five of the main factors had three levels, with each

having two degrees of freedom. Also, the study considered three interaction terms. Thus, the total sum of degrees of freedom, including the main factors as well as the interaction terms, was 20. Therefore, based on the 20 degrees of freedom, the  $L_{27}$  orthogonal array suited the present requirements as it had 26 degrees of freedom. The remaining 6 degrees of freedom were assigned as random error. The 27 trial conditions represented by Taguchi's  $L_{27}$  are given in Table 2. The dummy treated levels are marked by using \* against the repeated level.

**Table 2.** Experimental design and Results of experiments

Exp. No	Workpiece material	Electrode material	Electrode polarity	Pulse on time ( $\mu$ s)	Pulse current (A)	Pulse of time ( $\mu$ s)	Powder concentration (g/l)	TWR	
								$\overline{TWR}$	S/N
1	SKD61	Cu	-	5	8	38	0	1,95	-5,87
2	SKD61	Cu	+	10	4	57	10	2,01	-6,85
3	SKD61	Cu	-*	20	6	85	20	1,49	-3,57
4	SKD61	Cu*	+	10	6	85	0	4,42	-12,92
5	SKD61	Cu*	-*	20	8	38	10	4,36	-12,80
6	SKD61	Cu*	-	5	4	57	20	0,05	24,56
7	SKD61	Gr	-*	20	4	57	0	11,49	-21,21
8	SKD61	Gr	-	5	6	85	10	9,93	-19,95
9	SKD61	Gr	+	10	8	38	20	19,62	-25,85
10	SKD11	Cu	+	20	4	85	0	2,01	-61,87
11	SKD11	Cu	-*	5	6	38	10	1,17	-14,85
12	SKD11	Cu	-	10	8	57	20	3,56	-11,03
13	SKD11	Cu*	-*	5	8	57	0	2,25	-7,34
14	SKD11	Cu*	-	10	4	85	10	0,13	16,98
15	SKD11	Cu*	+	20	6	38	20	1,49	-3,83
16	SKD11	Gr	-	10	6	38	0	7,43	-17,67
17	SKD11	Gr	+	20	8	57	10	14,07	-22,98

18	SKD11	Gr	-*	5	4	85	20	5,49	-14,81
19	SKT4	Cu	-*	10	6	57	0	0,58	43,49
20	SKT4	Cu	-	20	8	85	10	5,07	-14,11
21	SKT4	Cu	+	5	4	38	20	2,90	-9,29
22	SKT4	Cu*	-	20	4	38	0	0,27	10,40
23	SKT4	Cu*	+	5	6	57	10	4,71	-13,49
24	SKT4	Cu*	-*	10	8	85	20	4,41	-12,92
25	SKT4	Gr	+	5	8	85	0	4,53	-13,13
26	SKT4	Gr	-*	10	4	38	10	9,04	-19,20
27	SKT4	Gr	-	20	6	57	20	14,58	-23,35

### 3. Results and discussion

#### 3.1 Result of experiments

TWR of each sample is calculated from weight difference of tool electrode before and after the performance trial, which is given by (4). The results for TWR for each of the 27 treatment conditions with each experiment was repeated three times. The results were processed by Minitab 17 to determine the mean value of the machining characteristics as well as the coefficient, S/N. The results are given in Table 3.

$$TWR = \frac{T_i - T_f}{\rho_T \cdot t} \cdot 1000 \text{ mm}^3 / \text{min} \quad (4)$$

Where

$T_i$  - Initial weight of tool electrode (g).

$T_f$  - Final weight of tool electrode (g).

$t$  - Time period of trails in minutes ( $t = 20\text{min}$ ).

$\rho_T$  - Density of tool electrode.

#### 3.2 Optimal design for TWR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratios have been calculated to identify the major contributing factors and interactions that cause variation in the TWR. TWR is 'Lower is better' type response which is given by (3).

An analysis of variance (ANOVA) was verified for the signal to noise ratio of both the main and and interaction terms. The F values of the parameters have shown which parameters were the most influential on providing the optimal values of the TWR. Table 3 shows the ANOVA for S/N ratio for TWR at 90% confidence interval. The electrode material (F value 25.48), current (F value 4.71), interaction between workpiece and powder concentration (F value 3.51) factors that affects the TWR. All remaining factors and the interactions are insignificant to affect TWR, table 9. It is observed that the electrode material is the most significant factor which contributes TWR followed by current and AxG, table 4.

**Table 3.** ANOVA for S/N ratio of TWR

Sources	DOF	SS	V	F	F <sub>table</sub>	P
Workpiece material (A)	2	29,64	14,84	0,41	3,46	-
Electrode material (B)	1	1567,45	1567,47	<b>25,48</b>	3,77	40,46
Electrode polarity (C)	1	185,40	185,4	3,01	3,77	-
Pulse on time (D)	2	77,88	38,94	0,63	3,46	-
Current (E)	2	579,67	289,86	<b>4,71</b>	3,46	14,82
Pulse of time (F)	2	3,85	1,93	0,03	3,46	-
Powder concentration (G)	2	33,03	16,97	0,28	3,46	-
AxB	2	45,16	22,58	0,37	3,46	-
AxG	4	864,34	216,08	<b>3,51</b>	3,18	22,63
BxG	2	19,7	9,85	0,16	3,46	-
Error	6	369,04	61,51	-	-	-
Total	26	3775,20	-	-	-	-
e pooled	19	763,7	40,19	-	-	-

**Table 4.** Response table for S/N ratio of TWR

Level	Input parameters						
	A	B	C	D	E	F	G
1	-7,597	-3,636	-7,170	-6,760	-2,847	-9,514	-7,733
2	-9,389	-19,799	-12,729	-9,460	-10,215	-8,595	-10,434
3	-10,084	-	-	-10,850	-14,008	-8,960	-8,902
Delta	2,487	16,163	5,559	4,091	11,16	0,919	2,701
Rank	<b>6</b>	<b>1</b>	<b>3</b>	<b>4</b>	<b>2</b>	<b>7</b>	<b>5</b>

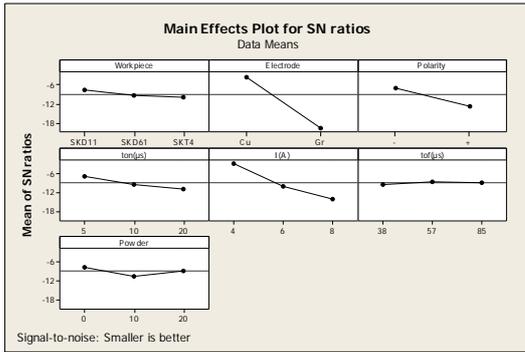


Figure 2. Main effects plot for S/N of TWR

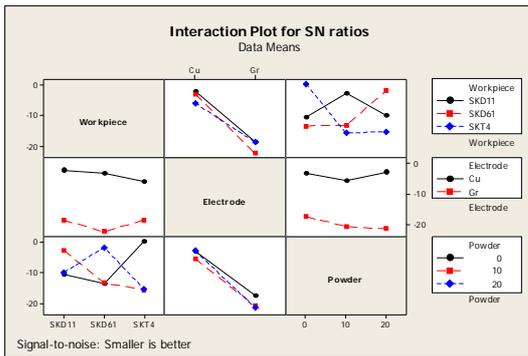


Figure 3. Interaction plot for S/N of TWR

The image given in Figure 2 shows the influence of the process parameters on the S/N factor of the TWR. These results showed that SKD11 steel materials, copper electrode materials, cathode polarization, time pulse of 5  $\mu$ s, current of 4 A, pulse of 57  $\mu$ s, and concentration of titanium powder of 0 g/L have a positive influence on the S/N factor of the TWR. These parameters greatly impacted the optimal results of the TWR. The image shown in Figure 3 illustrates the influence of the interaction between the parameters on the S/N of the TWR. Results indicated that interaction of SKD11 steel with Cu electrode materials, the interaction of SKT4 steel with titanium powder concentration of 0 g/L, the interaction of the Cu electrode materials with titanium powder concentration of

20 g/L were the interactions with the strongest influence on the S/N factor of the TWR.

*Estimated value of the  $\overline{TWR}$  at optimal conditions:* Reasonable process parameters of the TWR consisted of the following: A2, B1, C1, D2, E1, F2, and G2, of which two electrode material parameters (B) and current (E) had a strong influence on the TWR. The TWR's value was determined by the formula given in equation (5):

$$\mu_{B_2, E_3, G_1, B_2 \times G_1} = \overline{TWR}_{op} = \overline{B_1} + \overline{E_1} + \overline{A_3 \times G_3} - 2 \times \overline{T} \quad (5)$$

In this equation,  $\overline{B_1} = 2.383 \text{ mm}^3/\text{min}$ ;  $\overline{E_1} = 3.713 \text{ mm}^3/\text{min}$ ;  $\overline{A_3 \times G_3} = 7.30 \text{ mm}^3/\text{min}$ ;  $\overline{T} = 5.152 \text{ mm}^3/\text{min}$ . Consequently,  $\overline{TWR}_{op} = 2.383 + 3.713 + 7.30 - 2 \times 5.152 = 3.092 \text{ mm}^3/\text{min}$ .

Furthermore, the predicted confidence interval for the confirmation experiments was  $0.69 \text{ mm}^3/\text{min} \leq \overline{TWR}_{op} \leq 5.492 \text{ mm}^3/\text{min}$  with  $CI_{CE} = \pm 2.4$ . Additionally, the 90% confidence interval of the population was  $2.542 \text{ mm}^3/\text{min} \leq \overline{TWR}_{op} \leq 3.642 \text{ mm}^3/\text{min}$  with  $CI_{POP} = \pm 0.55$ .

*Confirmation Experiments:* Confirmation Experiments were conducted with the process parameters determined through calculations of the SKD11 workpiece material, the Cu electrode, the electrode polarization agreement, pulse duration of 10  $\mu$ s, a current of 4 A, the horizontal development pulse of 57  $\mu$ s, and powder concentration of 10 g/L. The results of the TWR = 2,93 mm<sup>3</sup>/min, and the difference between the calculated results and the experimental results was 4.1%.

#### 4. CONCLUSIONS

From the experimental work, an optimal set of process variables that yields the optimum quality features to machined parts produced by PMEDM using titanium powder has also been obtained. The use of the Taguchi method to optimize individual quality TWR of machining process was refined by. In S/N ratio, the electrode material is the most significant in affecting TWR followed by current, interaction between workpiece and powder concentration. The best results for TWR would be suggested if SKD11

workpiece machined at current 4 Amp and pulse on time 10  $\mu$ sec and pulse of time 57  $\mu$ s, with copper electrode and powder concentration of 10 g/l. The mean value with 90% confidence interval was found to be  $3.092 \pm 0.55$  mm<sup>3</sup>/min. The optimal sets of process parameters were obtained for various performance measures using Taguchi's design of experiment methodology. The summary results of predicted optimal values of the responses and their confidence intervals (both for confirmation experiment and population).

## Tối ưu hóa lượng mòn điện cực trong PMEDM sử dụng bột Titan bằng phương pháp Taguchi khi gia công thép làm khuôn

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### TÓM TẮT

Gia công tia lửa điện với dung dịch điện môi có trộn bột (PMEDM) là một công nghệ phức tạp. Phương pháp này được điều khiển bởi rất nhiều các thông số công nghệ. Trong đó, mỗi thông số có ảnh hưởng khác nhau đến chất lượng của quá trình gia công. Chất lượng của quá trình gia công tia lửa điện (EDM) được đánh giá bởi các đặc trưng công nghệ như: năng suất gia công (MRR), lượng mòn điện cực (TWR) và nhấp nhô bề mặt

( $R_a$ ). Trong bài báo này, TWR trong PMEDM sử dụng bột Titan là đối tượng được tối ưu hóa. Phương pháp Taguchi được sử dụng để đánh giá ảnh hưởng của các thông số công nghệ: vật liệu điện cực, vật liệu phôi, sự phân cực điện cực, thời gian phát xung, thời gian ngừng phát xung, cường độ dòng điện và nồng độ bột Titan. Phân tích Taguchi đã xác định được TWR tối ưu với trị số công nghệ tương ứng thông qua hệ số S/N của

nó. Vật liệu điện cực là thông số có ảnh hưởng mạnh nhất đến hệ số S/N của TWR. Trị số tối ưu  $R_{atoiuu} = 3,092 \text{ mm}^3/\text{phút}$  và kết quả tối ưu đã

**Từ khóa:** EDM; PMEDM; TWR, Phương pháp Taguchi; Hệ số S/N.

được thực nghiệm kiểm chứng cho độ chính xác phù hợp.

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