International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Investigation of Tool Wear Rate in Powder-Mixed EDM for Processing Ti6Al4V Alloy

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Abstract— *This paper investigates the copper tool wear rate (TWR) in Electrical discharge machining (EDM) using a Ag powder mixed dielectric for machining Ti6Al4V alloy. Initially, a Box–Behnken experimental design based on response surface methodology (RSM) was employed to evaluate the effects of key process parameters, including discharge current (I_p), pulse on time (T_{on}), and powder concentration (C_p), on the tool wear rate - TWR. A total of fifteen experimental runs were conducted to analyze the influence of these parameters on TWR. Subsequently, the relationship between the input technological parameters and TWR was established through a second-order mathematical model. The adequacy and statistical significance of the developed model were evaluated using analysis of variance (ANOVA) at a 95% confidence level. The results of this study provide a systematic understanding of the influence of EDM process parameters on copper electrode wear behavior during powder-mixed EDM of Ti6Al4V alloy.*

Keywords— *EDM, PMEDM, Ag powder, TWR, Ti6Al4V.*

I. INTRODUCTION

Electrical discharge machining (EDM) is widely used in mechanical manufacturing for processing materials that are difficult to machine by conventional cutting methods. In EDM, material removal is achieved through a series of electrical discharges generated between the electrode and the workpiece, commonly using electrode materials such as copper, graphite, and aluminum [1]. The intense localized heat produced during the discharge process leads to melting and vaporization of material, which may reduce machining efficiency and adversely affect surface integrity and electrode life.

Due to its potential to enhance EDM performance, the introduction of conductive powder particles into the dielectric fluid has become a topic of growing research interest in recent years. This technique, known as powder-mixed electrical discharge machining (PMEDM), has been reported to enhance discharge stability by modifying the electric field distribution and plasma channel behavior within the machining gap [2]. Various powders, including Ti, Si, Cr, W and SiC, have been investigated in EDM processes with different electrode materials [3]. The presence of powder particles significantly influences the discharge mechanism and thermal energy distribution during machining.

Recent studies have primarily focused on PMEDM using Ag powder with copper electrodes for titanium alloys such as Ti6Al4V[4]. However, investigations on PMEDM employing Ag powder with copper electrodes for machining titanium alloys remain limited. Titanium alloys, especially Ti6Al4V, exhibit low thermal conductivity and high chemical reactivity at elevated temperatures, which can intensify electrode wear during EDM operations.

Therefore, controlling the tool wear rate (TWR) is crucial for ensuring machining accuracy and process stability. This study aims to evaluate the influence of key technological parameters on the copper electrode wear rate during PMEDM of Ti6Al4V alloy.

II. MATERIALS AND METHODS

A. Materials

This experiment uses Ti6Al4V alloy. Its chemical composition includes Ti(88-92)%, Al(5-6.5)%, V(3.5-4,5)%, Fe(<0,3)%. Ag powder (0121XH) has a grain size of 50 nm to 60 µm and a chemical composition of 99% Ag. The dielectric fluid used is Rosia oil Machine EDM-10 supplied by the manufacturer VHP. The tests were conducted on an EDM machine (CNC- 460 EDM) using copper electrodes (99% Cu) with reverse polarization.

B. Methods

In this experiment, the parameters was selected according to the configuration of the CNC-460 EDM machine model of Aristech Company. All Ti6Al4V alloy samples used in the experiments have dimensions of diameter × length = 18 × 35 mm, after going through turning and finishing operations, electrode material was red copper with diameter 25mm. Then, the workpiece and the electrode are carefully mounted on the CNC-460 EDM machine with a reverse polarity. The size of the dielectric tank is D×W×H = 330x420x350 mm, holding a maximum of 41 liters of dielectric fluid. After that, Ag powder is added to the dielectric fluid.

To evaluate TWR, the experiment uses a PR model PR-3003 from Ningbo Oriental Scientific Instrument - China electronic balance (0.001 resolution, Figure 1e) to weigh the mass of the workpiece and electrode, before and after the machining process, as depicted in Equation 1. Processing time is calculated as the time it takes to cut the sample from a length size of 35 mm to 34.7 mm.

$$TWR\left(\frac{mg}{min}\right)=\frac{m_1 - m_2}{t} \qquad (1)$$

where, m_1 and m_2 are the mass of the copper tool electrode before and after machining, respectively, t is the processing time.

Fig. 1. Equipment, tools, and materials used in the experiment.

TABLE 1. The levels of process parameters.

Variables of process parametric	Levels		
pulse on time TON (µs)	50	100	150
Electrical discharge current Ip (A)	2	4	6
Concentration of Ag powder Cp (g/l)	0	4	8

In this study was to evaluate the influence of several process parameters on the electrode wear rate (TWR). The Box–Behnken design in response surface method (RSM) [9,10] was used to evaluate the influence of three variables on the objective function, as it is cost-effective by reducing the number of experiments while still providing an accurate and reliable predictive model for processes involving three to ten factors. Among the electrical parameters, the on-time pulse duration (T_{on}), discharge current (Ip), and silver powder concentration (C_p) were selected because they have the most significant influence on the objective function, namely the electrode wear rate (TWR) [9-12]. Based on the controller configuration and the actual machining capabilities of the CNC-460 EDM machine, the electrical parameters were selected according to Table 1, while other electrical variables, such as gap voltage and off-time pulse duration, were kept constant at 120 V and 50 µs.

TABLE 2. Trial matrix and data of output.

Trials	Input variables			Responses
	I_p(A)	T_{on}(µs)	C_p(g/l)	TWR(mg/min)
1	6	150	4	0.934
2	4	150	8	0.433
3	2	100	8	0.094
4	2	150	4	0.171
5	4	100	4	0.684
6	4	100	4	0.686
7	2	100	0	0.296
8	6	100	8	0.706
9	6	100	0	1.010
10	6	50	4	0.599
11	4	50	8	0.236
12	4	100	4	0.688
13	4	150	0	0.770
14	2	50	4	0.083
15	4	50	0	0.590

Table 2. The trial matrix with the parametric variables and response data is described in Table 2 and was used to establish the regression model for TWR. At each technological regime, the sample and electrode were measured three times before and after machining. The average values were taken, and the results are shown in Table 2.

III. RESULT AND DISCUSSION

A. Evaluate the influence of process variables on TWR.

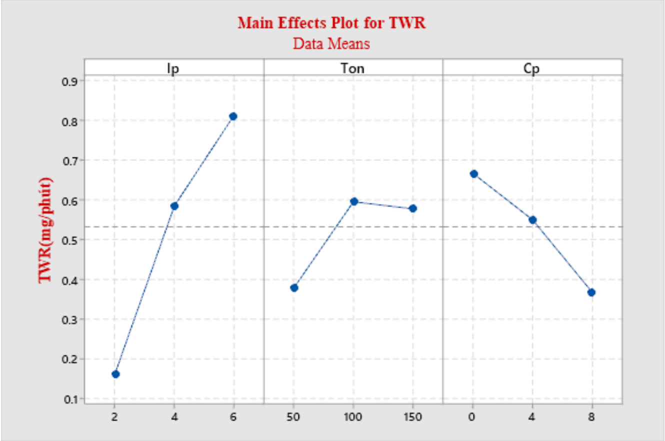

Fig. 2. Impact of control parameters on TWR.

Fig. 2 shows the main effects plots indicate that the electrode wear rate (TWR) is significantly influenced by the technological parameters I_p, T_{on}, and C_p. In general, TWR increases markedly with an increase in the discharge current Ip due to the higher discharge energy and thermal load imposed on the electrode. Pulse on time Ton affects TWR by extending the duration of the plasma channel, thereby increasing the total energy transferred to the electrode; however, this trend tends to reach saturation at higher T_{on} values [5]. In contrast, powder concentration C_p plays a regulating role, with TWR decreasing at intermediate C_p levels and increasing again when C_p exceeds the optimal value [4]. According to Table 3, the effects of I_p, C_p, and T_{on} TWR are 68.78%, 14.51%, and 7.26%, respectively.

The combined impact of the control parameters on TWR is indicated in Figs. 3a–c. TWR augments with an increment in the entire investigation space of I_p, T_{on}, and C_p, which are considered in Figs. 3a- c. According to Fig. 3a, TWR achieves the minimum value with C_p and T_{on} in the range of 4 g/l to 8 g/l and 50µs to 100µs, while TWR achieves the maximum value with C_p and T_{on} in the range of 0 g/l to 5 g/l and 75 µs to 150µs. For the combined influence of I_p and C_p (Fig.3b), TWR gets the minimum value with I_p and C_p in the range of 2A to 3A and 5g/l to 8g/l, while TWR obtains the maximum value with I_p and C_p in the range of 4A to 6A and 0g/l to 3g/l. Finally, the combined influence of T_{on} and I_p (Fig.3c), TWR gets the minimum value with T_{on} and I_p in the range of 50µs to 100 µs and 2A to 3A, while TWR obtains the maximum value with Ton and Ip in the range of 80µs to 150µs and 5A to 6A.

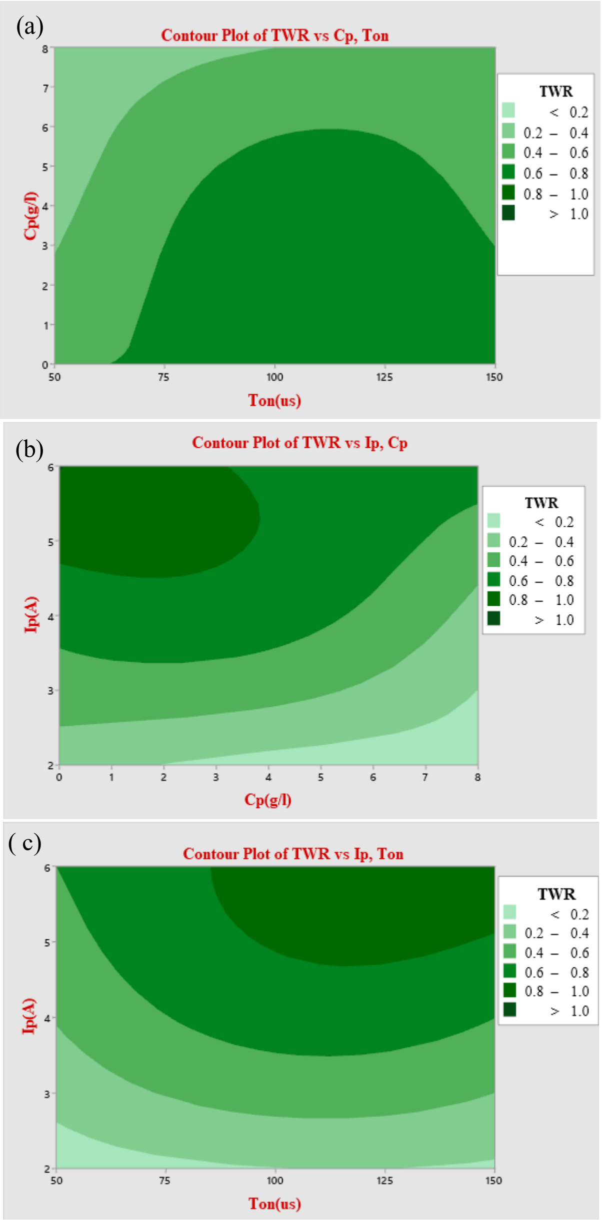

Fig. 3. The combined influence of control parameters on TWR : (a) C_p and T_{on}, (b) I_p and C_p, and (c) I_p and T_{on}.

B. Establishing the prediction model

To establish the mathematical model of TWR, a regression model in quadratic form was proposed, and is defined by the equation (2): as follows

$$f(x)=l_0+\sum_{i=1}^{n} l_i x_i+\sum_{i=1}^{n} l_{ii} x_i^2+\sum_{i<j}\sum_{j=2}^{n} l_{ij} x_i x_j \qquad (2)$$

where, λ_0, λ_i, λ_{ii}, and λ_{ij} are the coefficients of the regression models; x_i and x_j are process parameters; the variable number is n with $n = 3$; and the output property is $f(x)$ – TWR.

In this study, the coefficients and regression models were calculated and established using Design Expert software version 12. The predictive model for TWR is described as follows.

$$\begin{aligned}TWR&=-0.817625+0.0333812I_p+0.009785T_{on}\\&-0.002031C_p-0.02750I_p^2-0.000052T_{on}^2\\&-0.0003094C_p^2-0.000618I_pT_{on}\\&-0.003188I_pC_p+0.000021T_{on}C_p\end{aligned} \qquad (3)$$

C. Forecasting model evaluation

The accuracy of the TWR forecasting model was analyzed by analysis of variance (ANOVA) with a confidence level of 95% and a significance level of 5% used for evaluation, the results are shown in Table 3. Therefore, the coefficients that are significant for the TWR forecasting model include : I_p, T_{on}, C_p, $I_p \times T_{on}$, I_p^2, C_p^2. The R^2 value of the model indicates how closely the predicted values match the experimental values. In this model Adeq Precision = 37,4676 is greater than 4, indicating that the proposed TWR model is appropriate. The results (as indicated in Table 3) revealed that I_p had the most robust influence on the TWR and also showed that T_{on} had the least impact on TWR.

TABLE 3. ANOVA for predictive model of TWR

Source	SS	MS	F-value	p-value	Contribution	Remark
Model	1.23	0.1365	141.35	< 0.0001	99.61	significant
I_p	0.8483	0.8483	878.7	< 0.0001	68.78	
T_{on}	0.08	0.08	82.87	0.0003	6.49	
C_p	0.1791	0.1791	185.53	< 0.0001	14.51	
$I_p \times T_{on}$	0.0153	0.0153	15.8	0.0106	1.24	
$I_p \times C_p$	0.0026	0.0026	2.69	0.1616	0.21	
$T_{on} \times C_p$	0.0001	0.0001	0.0748	0.7954	0.01	
I_p^2	0.0447	0.0447	46.28	0.001	2.89	
T_{on}^2	0.0617	0.0617	63.9	0.0005	4.75	
C_p^2	0.009	0.009	9.37	0.0281	0.74	
Lack of Fit	0.0048	0.0016	401.56	0.0025	0.39	significant
R^2 = 0.9961; Adjusted R^2 = 0.9890; Predicted R^2 = 0.9374, Adeq Precision = 37.4676						

IV. CONCLUSION

This study investigated the influence of key process parameters on the total wear rate (TWR) of copper electrodes during powder mixed discharge machining (PMEDM) of Ti6Al4V alloy using silver powder. Based on the main effect plot and contour analysis, it was found that TWR increased significantly with increasing discharge current (I_p) and pulse duration (T_{on}). Among the parameters studied, I_p had the strongest influence on TWR at 68.78%. Conversely, powder concentration (C_p) played a regulating role in the discharge process. As C_p increased from 0-8 g/l, TWR decreased, and the decrease in TWR slowed down when C_p > 8 g/l. This can be extended to the fact that increasing C_p to higher levels can slow down electrode wear, significantly increasing the effect of TWR reduction. The influence of C_p on TWR was 14.51%. The results clearly show that proper control of I_p, T_{on}, and C_p is essential for managing electrode wear during the PMEDM process of Ti6Al4V alloy.

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