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Optimizing the Tool Wear Rate When Machining 9XC Steel in the EDM Process Mixing Tungsten Compound Powder by Desirability Approach Method

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Abstract**—** *In this paper, the tool wear rate (TWR) when machining 9XC steel in the EDM process with tungsten compound powder mixed was explored. The influence of key process variables, including peak current (I_p), pulse on time (T_{on}) and powder concentration (C_p) on TWR was shown through the implementation 15 experiments followed the Box - Behnken design in Response Surface Methodology (RSM), set up a full mathematical model for TWR using Minitab software version 21, then applied analysis of variance (ANOVA) with 95% confidence and a significance level of 5% to evaluate the accuracy of the TWR development model. The accuracy of the developed model has been verified by the values of the coefficients being $R^2=0.9997$; Adjusted $R^2=0.9992$; Predicted $R^2=0.9957$. Finally, the Desirability Approach (DA) method was used to optimize the process variables for reaching TWR_{min}. The results show that the minimal TWR is 0.0005317 g/min at $I_p=4$ A, $T_{on}=150$ µs and $C_p=6$ g/L.*

Keywords**—** *EDM, PMEDM, tungsten compound powder, TWR, DA.*

I. INTRODUCTION

Electro-Discharge Machining (EDM) is one of the typical machining methods for machining metals or alloys with high hardness such as Inconel 718, Hastelloy, SKD61, etc., and is characterized by its contactless machining process. Besides the outstanding advantages, the EDM process also has some limitations such as high tool wear rate, low material removal rate, and low surface quality. The above limitations of the EDM process have been overcome by adding conductive powders to the insulating dielectric fluid, known as powder-mixed electro-discharge machining (PMEDM). The machining performance has been improved because the insulating ability of the dielectric fluid has been reduced. At the same time, the electrode gap and spark intensity have been increased when conductive powder is mixed into the dielectric fluid during the spark discharge process [1][2][3][4]. In addition to improved machining efficiency, the surface quality of the sample such as microhardness, surface roughness and surface morphology are also improved in a good trend thanks to the spark discharge process becoming more stable [5][6][7].

In 1980, the first study on the effect on surface quality and machinability of samples in the PMEDM process when adding Al, Fe, and C powders to the dielectric fluid was reported [8]. Since then, many subsequent studies on different types of electrode materials and powders have been published. The combination of TC powder and ultrasonic tool in the EDM process when processing Al-Zn-Mg material was studied by Chen and Lin [9]. The results revealed that the surface roughness, the microhardness, the material removal rate (MRR), and the tool wear rate (TWR) are both improved compared to conventional EDM processes. S. Tripathy and D. Tripathy in their study [10] showed that the microhardness, microcracks and surface morphology of H-11 steel were improved with the participation of Cr powder in EDM process. At the same time, in the previous study [11] by the same group of authors, when using Cr powder to evaluate the effects on MRR, TWR, EWR and surface roughness of H-11 steel in the EDM process, the Taguchi method combining The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) technique and gray relational analysis (GRA) was applied to evaluate and optimize parameters, the result provided a set of process parameters that positively affect machining performance and sample surface roughness.

Van Tao Le in research [12] has shown that sample surface roughness is reduced by 57.984%, surface morphology is improved (smooth surface, few microcracks) and microhardness of the surface layer of the sample increased by up to 129.167% as compared to the conventional EDM process for SKD61 steel when using tungsten compound powder, combined with reasonable technological parameters. At the same time, in the later report [13], tungsten compound powder added to the EDM process to machine AISI H13 steel in the semi-finishing process was used by the author. As a result, the peak current (I_p), pulse on time (T_{on}) and powder concentration (C_p) have a great influence on machining performance (including MRR and TWR) and recast layer properties, specifically MRR and TWR tend to increase when I_p, T_{on}, and C_p increase, while recast layer thickness (RLT) formed by PMEDM decreases by 48.982% compared to EDM. The study [14] by Hossain et al. showed that MRR, TWR, microhardness, microcracks, surface roughness of mild steel billet samples and pure copper tool electrodes were all improved when using CeO_2 powder mixed in purified water. Prihandana et al. with the aim of finding a solution to increase the material removal rate without reducing surface quality, mixed micro-MoS_2 powder into the dielectric fluid, combined with the use of ultrasonic vibration during µ-EDM process in their research [15]. The results showed that the MRR increased significantly, and the sample surface quality

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improved significantly when there were no black carbon spots on the surface.

Al powder was used, along with changing input parameters such as current, pulse on time, powder concentration, and powder size to compare and evaluate the output characteristics between EDM and PMEDM processes. In the study [16] by Jabbaripour et al., the authors showed that the MRR increased by 54% and Al powder improved the surface roughness of γ-TiAl alloy samples by about 32% as compared to the EDM process. Singh in his research conducted many experiments with T1 steel sample to optimize the machining parameters related to machining performance of the PMEDM process and showed that: with input machining parameters including peak current, pulse on time, electrode material, and powder concentration, copper tool electrodes produced maximum MRR and minimum TWR, in contrast to graphite tool electrodes. Thereby, machining efficiency increases significantly as compared to conventional EDM process [17]. Recent trends in the selection and research of workpiece and powder materials are shown in Fig. 1 and Fig. 2 [18].

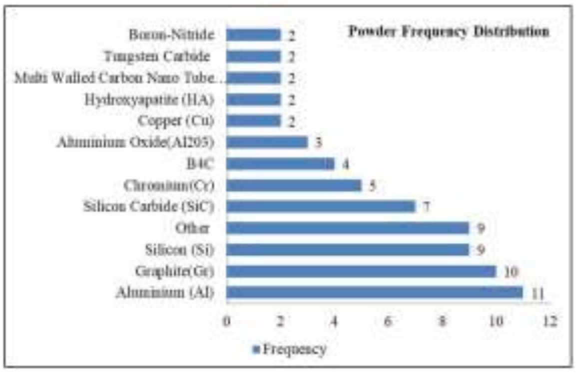
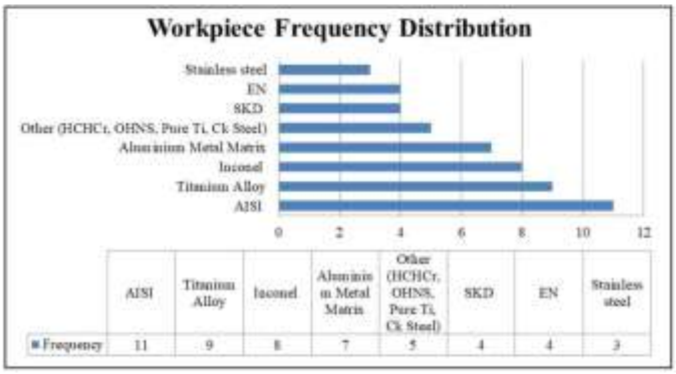


Fig. 1. Distribution frequency of mixed powder materials [18].



	AISI	Titanium Alloy	Inconel	Aluminium Metal Matrix	Other (HCHCr, OHNS, Pure Ti, Ck Steel)	SKD	EN	Stainless steel
▪ Frequency	11	9	8	7	5	4	4	3

Fig. 2. Distribution frequency of workpiece material [18].

As mentioned above, there have been many studies with different powders and electrode materials in the EDM process to achieve specific goals for different applications. However, studies on the tool wear rate (TWR) when adding tungsten compound powder to the dielectric fluid for 9XC alloy steel processed by the PMEDM process are still limited. Tungsten compound powder is a metal element with good resistance to oxidation, acid and alkali corrosion and has a high melting temperature (about 3422°C), low thermal expansion and high durability. 9XC steel has high hardness and hardness due to the content of Si and Cr elements. Besides, 9XC steel also has good toughness, stability when tempered and small deformation during heat treatment, so it is used to produce tools such as drill bits, threading tools, boring tools, and molds. stamping. Therefore, this study aims to analyze and evaluate the influence trends of process parameters including peak current (I_p), pulse on time (T_{on}), and powder concentration (C_p) on TWR during the EDM process with tungsten compound powder. In addition, to improve machining accuracy, in this study, the optimal domain of process variables to achieve TWR_{min} was found.

II. MATERIALS AND METHODS

A. Materials

This experiment uses 9XC steel imported from China. Its chemical composition includes 0.85%C-1.4%Si-1.2%Cr-0.2%Cu-0.03%P-0.15%Mo-0.35%Ni-0.03%S-0.4%Mn-0.1%W-0.13%V-0.03%Ti-balanced Fe (% weight). The dielectric fluid was EDM 2 oil supplied by the manufacturer Shell. Tungsten compound powder has a chemical composition including 5.56%C-11.9%Co-0.02%Fe-82.5%W-0.02% other components with code WC-727-6 provided by manufacturer Praxair Surface Technologies which was used in this experiment. Particle diameter is less than 31 µm.

B. Methods

The electric discharge machine with model CNC-460 EDM of Aristech Company was used for machining in this experiment. All 9XC steel samples used in the experiments have dimensions of diameter × length = 20 × 50 mm, after going through turning and finishing operations. They are then securely and carefully attached to the CNC-460 EDM machine to minimize errors during the PMEDM process. The dimensions of the tank are D × W × H = 420 × 320 × 320 mm, holding a maximum of 43 liters of dielectric fluid. Then, tungsten compound powder is added to the dielectric fluid in the tank.

Fig. 3. Machines, materials and tools used in the experiment.

To calculate TWR (g/min), the mass of the copper tool electrode is weighed before and after the PMEDM process, when the sample size is reduced from 50 to 49.5 mm (also the sample processing time) and calculated as follows

$$TWR\left(\frac{g}{min}\right)=\frac{m_1 - m_2}{machining\ time} \tag{1}$$

where, m_1 and m_2 are the mass of the copper tool electrode before and after machining, respectively, weighed by the SC638 electronic scale of Scaleloss - China (smallest division 0.01 g).

TABLE 1. The levels of process parameters.

Variables of process parametric	Levels		
I_p (A)	4	6	8
T_{on} (µs)	50	100	150
C_p (g/L)	0	10	20

The purpose of this study is to evaluate the influence of several process parameters on the tool wear rate (TWR) and optimize these parameters to yield the smallest TWR. When investigating the influence of 3 factors, the Box - Behnken model in RSM produces the most accurate and appropriate model for 3 factors as compared to other experimental statistical methods. At the same time, to save experimental costs by reducing the number of experiments, Box - Behnken experimental strategy in RSM was implemented. The process parameters are selected based on criteria and grounds: for electrical parameters, based on the controller settings configuration and the actual machining capabilities of the CNC-460 EDM electrical discharge machine. Among them, the peak current (I_p) and pulse on time (T_{on}) have a strong impact on machining performance in the PMEDM process [13][17][19] so they were selected. Through understanding the electrical and thermal properties of tungsten compound powder, combine the electrical parameters selected above to conduct exploratory tests, thereby selecting these powder concentration levels. The varying value levels of electrical parameters and different powder concentration levels in this experiment were selected as shown in Table 1, other parameters such as discharge voltage (120 V), pulse off time (50 µs) and electrode polarity (99% Cu tool electrode - cathode) were fixed in all experiments.

TABLE 2. Trial matrix and data of output.

Run	Process parameters			Output variable
	I_p (*A*)	T_{on} (*µs*)	C_p (*g/L*)	TWR (*g/min*)
1	8	50	10	0.001745420
2	6	50	0	0.000815603
3	4	100	20	0.000638405
4	6	150	0	0.000820490
5	8	150	10	0.001855000
6	8	100	20	0.001838490
7	6	100	10	0.000813730
8	4	150	10	0.000531700
9	4	100	0	0.000647312
10	6	100	10	0.000809890
11	6	50	20	0.000739063
12	8	100	0	0.001891320
13	6	100	10	0.000818857
14	4	50	10	0.000535684
15	6	150	20	0.000843717

Table 2 describes the experimental matrix with levels of input variables and response data, used to establish the regression model for TWR. The mass result of the tool electrode is the average value of three measurements, both before and after machining.

III. RESULT AND DISCUSSION

A. Establishing the prediction model

To establish the prediction model of output feature – TWR, a regression model of quadratic equation has been offered as follows

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

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 model were calculated and established using Minitab software version 21. The prediction model of TWR is described as follows

$$\begin{aligned} TWR &= 0.00255 - 0.000915 I_p + 0.000002 T_{on} \\ &- 0.000011 C_p + 0.0001 I_p^2 - 0.19274\times10^{-7} T_{on}^2 \\ &+ 3.8745\times10^{-7} C_p^2 + 2.8391\times10^{-7} I_p T_{on} \\ &- 5.4903810^{-7} I_p C_p + 0.4988310^{-7} T_{on} C_p \end{aligned} \tag{3}$$

B. Assessment of the development model

Analysis of variance (ANOVA) with a 95% confidence level and 5% significance level was used to evaluate the accuracy of the TWR development model, the results are shown in Table 3. p-values corresponding to the terms of the model are smaller than 0.05, this indicates that these model elements are meaningful. Therefore, the terms are significant for the TWR prediction model, including I_p, T_{on}, C_p, $I_p \times T_{on}$, $T_{on} \times C_p$, I_p^2, T_{on}^2, C_p^2. Through the coefficients "R^2", "Adjusted R^2", and "Predicted R^2", the accuracy of the developed model has been verified by the values of these coefficients being 0.9997, 0.9992, and 0.9957 respectively.

TABLE 3. ANOVA for predictive model of TWR

Source	SS	MS	F-value	p-value	Remark
Model	3.728E-06	4.142E-07	1991.13	<0.0001	significant
I_p	3.096E-06	3.096E-06	14885.88	<0.0001	significant
T_{on}	5.785E-09	5.785E-08	27.81	0.0033	significant
C_p	1.655E-09	1.655E-09	7.95	0.0371	significant
$I_p \times T_{on}$	3.224E-09	3.224E-09	15.50	0.0110	significant
$I_p \times C_p$	4.824E-10	4.824E-10	2.32	0.1883	not significant
$T_{on} \times C_p$	2.488E-09	2.488E-09	11.96	0.0181	significant
I_p^2	5.937E-07	5.937E-07	2853.94	<0.0001	significant
T_{on}^2	8.573E-09	8.573E-09	41.21	0.0014	significant
A_p^2	5.543E-09	5.543E-09	26.65	0.0036	significant
Lack of Fit	9.996E-10	3.332E-10	16.46	0.0578	not significant
R^2 = 0.9997; **Adjusted** R^2 = 0.9992; **Predicted** R^2 = 0.9957					

C. Evaluate the influence of manufacturing process variables on TWR

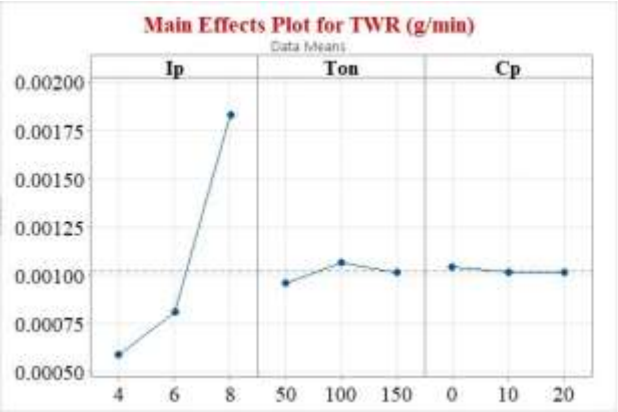
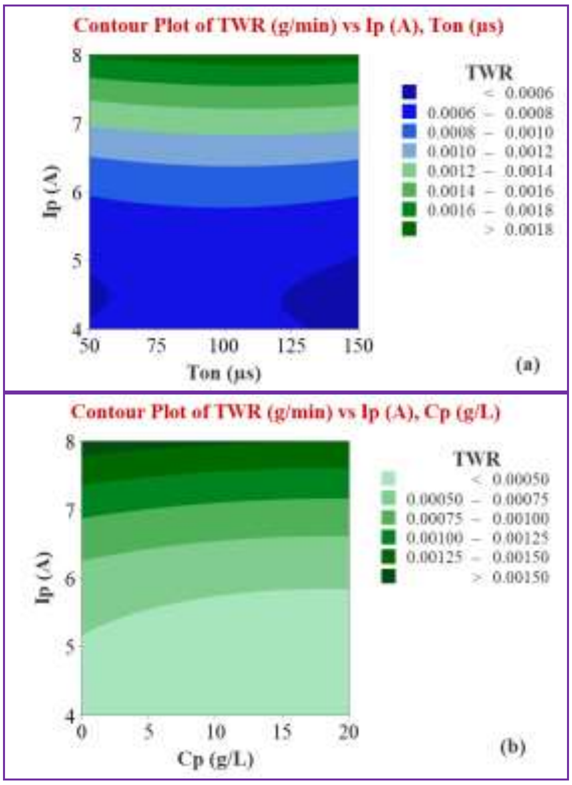


Fig. 4. Main influence of process parameters on TWR.

Fig. 4 shows the main impact of each process parameter on TWR, showing that TWR increases with increasing values of I_p over the entire design space domain. Meanwhile, increasing C_p tends to reduce TWR in the entire survey value range. In addition, TWR also increases in the value range of T_{on} from 50 to 100 µs and gradually decreases in the value range from 100 to 150 µs. The reason is that the energy of the spark increases as the current increases, causing TWR to increase. Meanwhile, when T_{on} is short, it reduces the ionization time of the dielectric liquid, which creates an unstable machining process. When T_{on} is long, the energy will be dispersed to many electrons and ions and reduce their bombardment energy, leading to a decrease in TWR.



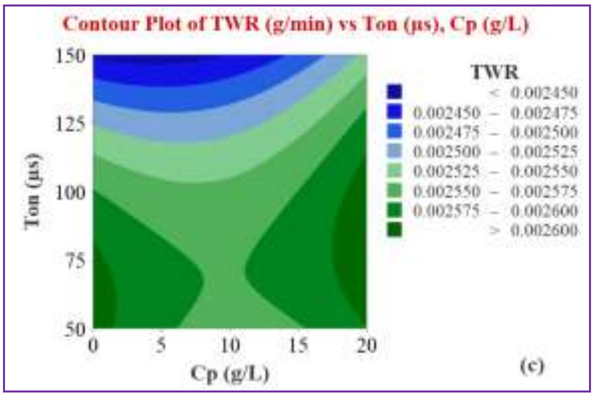


Fig. 5. The incorporated influences of process parameters on TWR: (a) I_p and T_{on}, (b) I_p and C_p, and (c) C_p and T_{on}.

The combined effect of process parameters on TWR is depicted in Fig. 5(a), Fig. 5(b), and Fig. 5(c). It is shown that TWR increases as I_p increases for all values of T_{on} and C_p (Fig. 5(a) and Fig. 5(b)), TWR has a small value when combining the value of large T_{on} with small I_p and C_p (Fig. 5(c)). It can be seen that increasing I_p leads to increased spark energy, making the tool electrode wear process become stronger [19]. In addition, prolonged T_{on} makes the plasma channel radius large, creating a large gas explosion pressure in the previous discharge, affecting the re-entry of powder particles into the machining area in the next discharge. leading to low powder particle density. As a result, the thermal energy formed in the discharge channel is reduced due to the reduction in the number of sparks [20]. Inappropriate amount of powder in subsequent machining will lead to short circuit or electric arc formation. The TWR will decrease because the thermal energy generated in the discharge channel and transmitted to the electrode material is reduced [12][19][21].

D. Optimization of the TWR

Desirability approach (DA) is one of the simplest and widely used methods to optimize process parameters and machining response. Specifically, in this experiment, the input parameters I_p, T_{on}, C_p are optimized to minimize the TWR output value. With this reaching, each output attribute (y_i) is converted into a unique desired function (d_i), $d_i \in [0, 1]$.

If the attribute is expected to minimize, d_i is determined as follows

$$d_i(y_i) = \begin{cases} 0, y_i < L \\ \left(\dfrac{H - y_i}{H - L}\right)^r, L \le y_i \le H \\ 1, y_i > H \end{cases} \qquad (4)$$

where, the upper and lower bound values of y_i are H and L, respectively. r is a parameter named by utilizers ($r > 0$) to depict the shape of d_i. In the end, the desired function D is defined as follows

$$D = \left(\prod_{i=1}^{n} D_i^{w_i}\right)^{\frac{1}{\sum w_i}} \qquad (5)$$

where w_i is the weight, $w_i > 0$ and $\sum_{i=1}^{n} w_i = 1$ with n being the number of attributes/responses.

Specifically, the weight of TWR is assigned as w_1. As a result, the set of optimized values obtained for the parameters using the DA technique is I_p=4 A, T_{on}=150 µs and C_p=6 g/L. The value of TWR corresponding to the optimal process variables is TWR=0.0005317 g/min.

IV. CONCLUSION

In this study, the machining performance (TWR) when machining 9XC steel using the EDM process with tungsten compound powder was investigated. Establishing a prediction model for machining performance, optimizing process parameters, and evaluating the influence of these parameters on TWR were performed. The study also used the Box-Behnken method in RSM to set up the experimental matrix, at the same time set up regression models and used ANOVA analysis of variance with 95% confidence level and 5% significance level to Evaluate the accuracy of the TWR development model. The results show that the regression models are highly accurate and can be used to study the influence of process parameters and predict the desired TWR in the entire survey domain. Through the desirability function approach (DA), the optimal response TWR=0.0005317 g/min corresponds to the process parameters I_p=4 A, T_{on}=150 µs and C_p=6 g/L was found. In future works, other machining performance parameters such as material removal rate MRR, surface roughness SR, as well as surface characteristics such as recast layer thickness, percent of micro-crack on surfaces and surface morphology of 9XC steel before and after heat treatment will be studied for application in the manufacturing industry.

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