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Evaluate the impact and Optimizing the Material Removal Rate of SKD11 steel when processed by EDM with powder mixing

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Abstract: In this study, material removal rate (MRR) when machining SKD11 steel in the EDM process with tungsten carbide 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 MRR was shown through the implementation 15 experiments followed the Box - Behnken design in Response Surface Methodology (RSM), set up a full mathematical model for MRR using Design expert vesion 12, then apply analysis of variance (ANOVA) with a 95% confidence level and a 5% significance to assess the adequacy of this model. The accuracy of the model has been validated with the coefficient values of R^2=0.9932; Adjusted R^2 = 0.9808; Predicted R^2 = 0.8930. Finally, the Desirability Approach (DA) method was used to optimize the process variables for reaching MRRmax. The results show that the highest MRR is 4.421 mg/min at I_p=8 A, T_{ON}=150 µs and C_p=10 g/l.

Keywords: EDM, PMEDM, tungsten carbide powder, MRR, DA.

I. INTRODUCTION

Tool steel is commonly used in the manufacturing industry to make tools for machining and shaping various materials, such as metals, wood, plastic, and other materials [1,2]. SKD11 tool steel is one of the important materials in advanced machining technology due to its characteristics like good durability, high load-bearing capacity, high dimensional stability after heat treatment, and especially outstanding wear resistance thanks to its high carbon and chromium content [3,4]. Due to such characteristics, they are widely used in long-lasting cold work applications that require very high wear resistance and high compressive strength, in cold stamping dies, in the automotive and aerospace industries. Despite being widely used in various industries, machining SKD11 tool steel is still a major concern for researchers due to significant tool wear, vibration during the machining process, and low material removal rates. Several methods have been studied to improve machining performance, one of which is electrical discharge machining (EDM). EDM is a material erosion process that mainly uses electrical energy and converts it into thermal energy through a non-continuous discharge cycle occurring between the tool and the workpiece in a dielectric environment. In the past, EDM was a pretty popular method compared to other machining techniques. However, significant limitations like low machining performance, time consumption, high costs, surface quality not meeting technical requirements, and applicability only to conductive materials restrict the use of EDM [5,6], this motivates researchers to improve methods to enhance machining performance, and one approach being studied is powder-mixed electric discharge machining (PMEDM). In PMEDM, fine powder particles are added to the dielectric fluid, and during the machining process, this mixture is introduced into the spark gap between the tool and the workpiece, which has been reported to enhance machining performance [7].

Adding the powder reduces the intensity and increases the spark gap, leading to more sparks, which makes it easier to get rid of the material [8]. The properties of the powder, such as particle size, density, and thermoelectric characteristics are some important factors that affect the machinability of the PMEDM process. In 1980, Erden and Bilgin [9] reported experimental and theoretical results on the effect of powder particles when mixed into the EDM dielectric. The powders, which include copper, aluminum, iron, and carbon are mixed into a solvent which is oil and the workpiece material is steel. The report results indicate that adding the powder into the solvent has increased the material separation rate. However, the report also mentioned that processing becomes unstable at high powder concentrations due to the occurrence of short circuits.

There have been several studies both domestically and internationally on different machining materials and powders mixed into solvents to achieve certain effects aimed at increasing MRR. However, studies on Material Removal Rate (MRR) when adding tungsten carbide powder to dielectric fluid for machining SKD11 steel are still limited. Therefore, this study aims to Evaluate the impact of technological parameters including peak-current (I_P), pulse-on time (T_{ON}), and powder concentration (C_P) on MRR, developing the predicted a model of MRR and find the optimal parameter domain to achieve the maximum MRR when machining SKD11 steel using the PMEDM method.

II. MATERIALS AND METHODS

2.1. Materials

This experiment uses SKD11 steel imported from Japan. Its chemical composition includes 1.5%C, 0.3%Si, 0.5%Mn, 12%Cr, 1%Mo, 0.35%Va and balanced Fe (% weight). Tungsten carbide powder (WC-727-6) has a grain size of 5 µm to 31 µm and a chemical composition of: W-82.5, C-5.56, Co-1.9, Fe-0.02, other-0.02 (by composition %). The dielectric fluid used is EDM oil 2 supplied by the manufacturer Shell. The tests were conducted on an EDM machine (CNC-460 EDM) using copper electrodes (99% Cu) with reverse polarisation.

2.2. Methods

In this experiment, the parameters was selected according to the configuration of the CNC-460 EDM machine model of Aristech Company. All SKD 11 steel samples used in the experiments have dimensions of diameter × length = 20 × 50 mm, after going through turning and finishing operations, electrode material was red copper with diameter 35 mm. 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 = 420x320x320 mm, holding a maximum of 43 liters of dielectric fluid. After that, tungsten carbide powder is added to the dielectric fluid.

Figure 1: (a) EDM CNC-460 machine, (b) the specimen material, (c) the tool electrode material, (d) the dielectric liquid, (e) the powder, and (f) electronic scale

The weight of the sample and the instrument electrode was measured using the SC638 electronic scale from Scaleloss - China (minimum division 0.01 g). The weight of the sample was weighed before and after the PMEDM process when the size was reduced from 50 to 49.6 mm and calculated as follows:

$$MRR(\frac{mg}{\min}) = \frac{M_1 - M_2}{t} \tag{1}$$

Where, M_1, M_2 are the mass of the workpiece before and after processing, t is the processing time.

Table 1: The levels of process parameters

Variables of process parametric	Levels		
T_{ON} (µs)	50	100	150
I_p (A)	4	6	8
C_p (g/l)	0	5	10

In this study, the Box-Behnken design in RSM [16,17] is used when assessing the influence of 3 variables on the objective function because it saves costs by reducing the number of experiments while providing the most accurate and suitable predictive model for processes with 3 to 10 factors. Among the electrical parameters, pulse-on time T_{ON}, peak-current I_p, tungsten carbide powder concentration C_p were selected because they had the strongest impact on the objective function MRR [10,11,12]. Based on the controller setting configuration and actual machining capability of the CNC-460 EDM machine, the electrical parameters are selected according to Table 1, other variables of the electrical parameters such as current voltage and pulse off time are fixed with the values of 120 V and 50 µs respectively.

Table 2: Trial matrix and data of output

Run	Process parameters			MRR (mg/phút)
	I_p (A)	T_{on} (µs)	C_p (g/l)	
1	8	100	10	4.3053
2	6	50	10	3.5154
3	8	50	5	3.863
4	6	150	0	3.1463
5	4	100	0	2.7448
6	8	100	0	3.85455
7	6	50	0	2.89244
8	6	150	10	3.6371
9	8	150	5	4.072
10	4	50	5	2.7259
11	6	100	5	3.1913
12	6	100	5	3.159
13	4	100	10	3.4707
14	4	150	5	3.29545
15	6	100	5	3.1676

Table 2 describes the experimental matrix with input variable levels and response data, used to establish the regression model for MRR. The results obtained are the average values of 3 measurements of the experimental material before and after machining.

III. RESULT AND DISCUSSION

3.1. Establishing the prediction model

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

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i<j} \sum_{j=2}^{n} b_{ij} x_i x_j + d \qquad (2)$$

Where, β_0, β_i, β_j and β_{ij} are coefficients of the predictive model; x_i, x_j are process variables; n is number of variables, with $n = 3$; δ: surplus, y: output properties.

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

$$\mathrm{MRR} = 3.24977 - 0.553067 \times \mathrm{I_P} + 0.008137 \times \mathrm{T_{ON}} + 0.065764 \times \mathrm{C_P} - 0.000901 \times \mathrm{T_{ON}} \times \mathrm{I_P} - 0.000132 \times \mathrm{T_{ON}} \times \mathrm{C_P} - 0.006879 \times \mathrm{I_P} \times \mathrm{C_P} + 4.08 \times 10^{-6} \times \mathrm{T_{ON}^2} + 0.07656 \times \mathrm{I_p^2} + 0.004598 \times \mathrm{C_P}^2 \qquad (3)$$

3.2. Forecasting model evaluation

Table 3: ANOVA for predictive model of MRR

Source	**SS**	**MS**	**F-value**	**p-value**	**Remark**
Model	3.12	0.3464	80.66	< 0.0001	significant
I_p	1.86	1.86	433.24	< 0.0001	significant
T_{ON}	0.1665	0.1665	38.77	0.0016	significant
C_P	0.6557	0.6557	152.7	< 0.0001	significant
$I_p \times T_{ON}$	0.0325	0.0325	7.57	0.0403	significant
$I_p \times C_p$	0.0189	0.0189	4.41	0.0898	not significant
$T_{ON} \times C_p$	0.0044	0.0044	1.02	0.3596	not significant
I_p^2	0.3463	0.3463	80.63	0.0003	significant
T_{ON}^2	0.0004	0.0004	0.0897	0.7766	not significant
C_p^2	0.0488	0.0488	11.36	0.0199	significant
Lack of Fit	0.0209	0.007	24.91	0.0388	significant
R^2 = 0.9932; **Adjusted R^2** = 0.9808; **Predicted R^2** = 0.8930, **Adeq Precision** = 28.7273					

The accuracy of the MRR 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 MRR 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 = 28.7273 is greater than 4, indicating that the proposed MRR model is appropriate.

3.3. Evaluate the influence of process variables on MRR

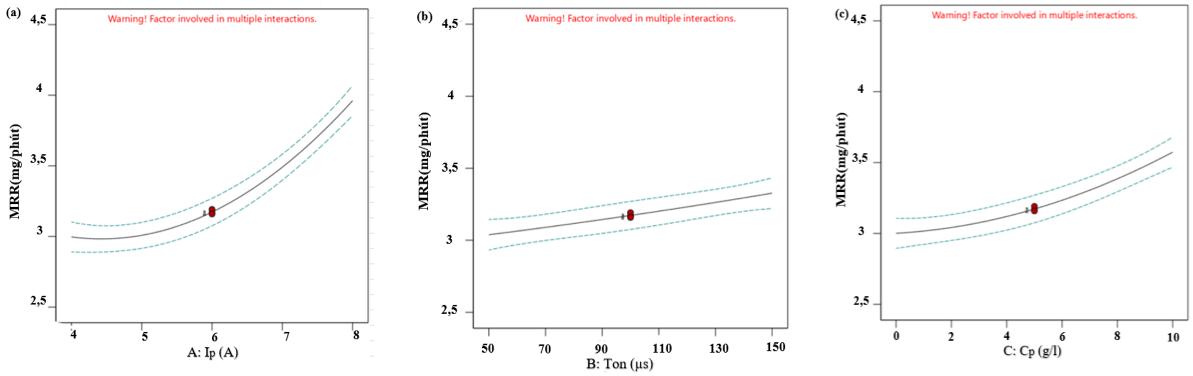

Figure 2: Main influence of process parameters on MRR

Figure 2 shows the main impact of each process parameter on MRR, we see that when I_p, T_{ON}, C_p increase, MRR increases in the entire design space. In which, according to table 3, the influence of I_p is the largest, followed by C_p and T_{ON}. The reason that when the peak-current I_p and pulse-on time T_{ON} increase, the energy of the electric spark during the machining process increases, leading to an increase in MRR [13,14]. At the same time, when the powder concentration increases, it leads to the formation of more sparks and the expansion of the machining area, leading to an increase in MRR [15].

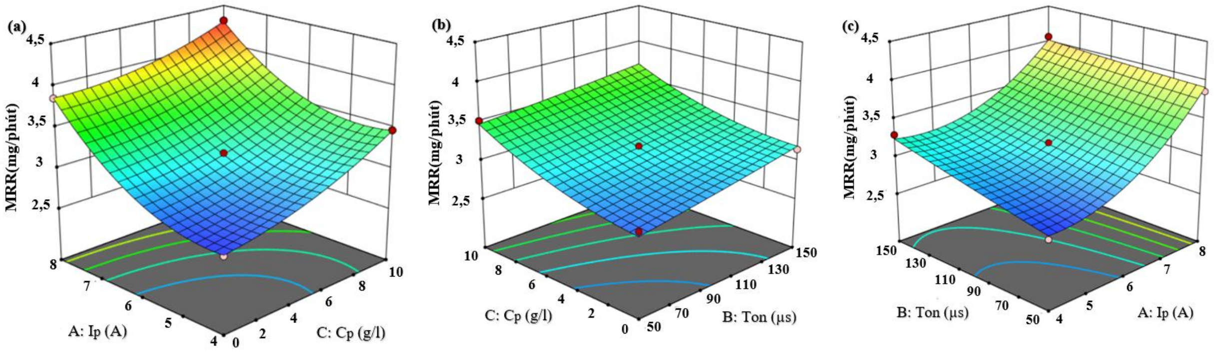

Figure 3: The influence of factor pairs I_p, Cp; C_p, T_{ON} and I_p, T_{ON} on MRR

The combined effect of the influence of process parameters on MRR is depicted in Figure 3. It is shown that MRR increases as I_P increases for all values of T_{ON} and C_P. This is explained, increasing I_p increases the spark energy, which increases the material removal ability. At the same time in the survey area, increasing the T_{ON} pulse-on time and C_p powder concentration will increase the number of powder particles appearing in the spark gap, leading to an increase in the number of sparks generated in one pulse and a decrease in the insulation of the dielectric solution, leading to an increase in MRR [12,15].

3.4. Optimization of the MRR

In this study, the desirability approach (DA) is used to optimize the process parameters I_p, T_{ON}, C_p to achieve the maximum MRR. To achieve this, each output attribute (y_i) is transformed into a unique desirability function (d_i), $d_i \in [0,1]$.

The desired attribute MRR is maximized, yi is calculated by formula (4):

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

Where, the upper and lower bound values of yi are H and L respectively. r is a user-named parameter (r > 0) to describe the shape of d_i. Finally the desired function is defined by the equation:

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

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

The result, the set of optimal parameters obtained using the DA technique (with D = 0.745) through Design Expert 12 software is I_p = 8 A, T_{ON} = 150 µs, Cp = 10 g/l. The corresponding MRR value for the optimized process variable is 4.421 mg/min.

IV. CONCLUSION

In this study, the material removal rate when machining SKD11 steel by EDM process with tungsten carbide powder was investigated. The study established a model to predict machining performance, optimized process parameters and evaluated the influence of these parameters on MRR. The study also used the BoxBehnken 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 MRR 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 MRR in the entire survey range. The DA technique was used to find the optimum MRR of 4.421 mg/min corresponding to the process parameters I_P = 8 A, T_{ON} = 150 µs and C_P = 10 g/l as shown. In the future, other performance parameters such as tool wear rate TWR or surface roughness SR will also be studied for broader applications in manufacturing.

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