Optimization of PMEDM Parameters for Improving MMR in Machining 90CrSi Steel - A Taguchi Approach

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Abstract. To overcome the limits of the electrical discharge machining (EDM) process, the nanoscale fine powder is added to the dielectric in a new machining method called powder mixed electrical discharge machining (PMEDM). In this research, the Taguchi approach has been applied to determine the effects of PMEDM parameters such as the powder concentration, the pulse-on-time, the pulse-off-time, the pulse current, and the server voltage to material removal rate (MRR) in hardened 90CrSi steel processing. L18 orthogonal array, signal to noise (S/N) ratio, and ANOVA were employed to plan and analyze the experiment. The pulse current was determined to be the factor that had the strongest impact on MRR. Moreover, an optimal EDM condition was found to improve MRR. The powder concentration of 3.5 g/l, the pulse-on-time of 6 µs, the pulse-off-time of 30 µs, the pulse current of 12 A, and the server voltage of 5 V resulted in maximum MRR.

Keywords: EDM · PMEDM · MRR · Taguchi method · ANOVA · SiC powder

1 Introduction

EDM is an advanced machining method that is commonly applied in industry. The advantage of EDM lies in the ability to process complex geometric shapes and materials that are difficult to machine by conventional machining methods. During EDM, the metal is removed by spark erosion principle [1, 2]. Sparks appear on a narrow gap between the electrode and the workpiece that takes place in the dielectric fluid [3–6]. Low processing productivity is a major problem for the EDM process. In addition, low surface quality, high roughness, and high tool wear rate are limitations of this machining method. In 1981, A. Erden and S. Bilgin published their scientific work on the role of impurities in electric discharge machining [7]. The authors suggested that

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the increase in the concentration of impurities led to a significant improvement in removal rate. Their findings are key to improving the performance of the EDM process. PMEDM has been proposed with a number of advantages such as improved roughness, high MRR, and low tool wear rate to replace the traditional EDM method [8–10]. During PMEDM, nano-sized fine powder is mixed in dielectric. EDM dielectric fluid functions as a spark conductor and discharge medium, and it is also used to remove eroded metal particles. The mixing of fine powder into the dielectric changed the discharge gap size, discharge transitivity, breakdown strength, and deionization of dielectric [6, 9]. The size of the discharge gap between the electrode and the machining surface is increased due to the decrease of the insulating strength of dielectric when adding the powder [11–16]. The enlarged size of the discharge gap facilitates the flushing of debris and short-circuiting. The uniform distribution of sparks and the stability of the discharge process lead to an increase in MRR [11, 17–19].

In a study conducted by Paramjit Singh et al. [19], the authors concluded that the PMEDM process parameters such as electric current, the material of the electrode, and the concentration of powder had a strong impact on MRR. Ojha, K. et al. conducted an investigation to determine the effects of PMEDM parameters on MRR and tool wear [20]. The conclusion was that pulse current, concentration of powder and electrode diameter were main factors affecting MRR and tool wear. In a study of Long, B. T. et al., an optimization of PMEDM parameters to improve the MRR was carried out. The authors confirmed that electric current, electrode material, and concentration of powder had the biggest impact on MRR [21]. PMEDM process of SKD61 steel was conducted in a research of Kobayashi et al. [22]. The results showed that a suitable amount of suspended silicon powder added increased MRR and reduced surface roughness. Similarly, H.K. Kansal optimized the PMEDM process by using the Taguchi method. He found that a sufficient amount of graphite powder added to the dielectric greatly increased MRR, reduced tool wear and improved roughness [23].

SiC powder added to the EDM dielectric has been applied in several studies. In [18], SiC powder concentration was reported as the main factor affecting particle transfer. A positive result was achieved in the study of Al-Khazraji when the author investigated the effect of PMEDM process on SiC powder on white layer, heat flux, and fatigue life in machining of AISI D2 steel [24]. In another research [25], Kuriachen, B. and J. Mathew emphasized that lower powder concentration results in an increase in MRR and an improvement of tool wear during machining of Ti-6Al-4 V. A similar result was provided in a study by Razak, M. A. et al. The authors argued that the application of SiC powder in the EDM process improved surface roughness, increased MRR, and reduced processing costs and time [2]. Various research works have been performed for enhancing the machinability of difficult-to-cut materials using various forms of EDM processes [26–36]. It was observed that the materials could be effectively produced using EDM processes.

Mechanical products with complex shapes and difficult-to-machine materials are challenges for traditional machining processes. In actual production, cylindrical-shaped parts are those that are difficult to machine. A typical example of this type is the tablet press punch as shown in Fig. 1. The face of the tablet press punch is concave with a complex profile. In advanced industrial countries, the tablet press punch is often machined by micro-milling. In developing countries, this punch is made by the benchwork with rather low productivity. Therefore, a machining method for making the tablet press punch proposed by our team is to use EDM with a hole-shaped electrode. The productivity of this process is also enhanced by the application of PMEDM [37].

Fig. 1. Tablet press punches [37]

In this work, an attempt was made to determine the influence of PMEDM parameters on the MRR in processing cylindrical shape parts made of 90CrSi steel (as tablet press punches) by using Taguchi approach. The optimum values of PMEDM conditions have been determined to achieve the maximum MRR. In addition, the efficiency of EDM with SiC powder-mixed dielectric has been found predominant when compared that of traditional EDM processes.

2 Experimental Procedure

In the study, the Taguchi method is used to find the optimal condition of the PMEDM process for maximizing MRR in hardened 90CrSi steel processing. In addition, an orthogonal array is selected to organize the experiment. The parameters of PMEDM process include the powder concentration (C_p), the pulse-on-time (T_{on}), the pulse-off-time (T_{off}), the pulse current (IP), and the server voltage (SV) as shown in Table 1. With the parameters and their levels, L18 array is chosen to design the experiment.

To measure the performance characteristics and calculate the impact of each input factor, a suitable type of signal to noise (S/N) and ANOVA analysis are employed. With the goal of maximizing MRR, the-bigger-is-the-better S/N type is applied and calculated as the following equation:

$$\frac{S}{N} = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \quad (1)$$

Where y_i is the data received by the experiments, n is the number of experiments.

Table 1. PMEDM parameters and their levels

Levels	Parameters				
	C_p (g/l)	T_{on} (µs)	T_{off} (µs)	IP (A)	SV (V)
1	0	6	14	4	3
2	2	10	21	8	4
3	2.5	14	30	12	5
4	3.5	–	–	–	–
5	4	–	–	–	–
6	4.5	–	–	–	–

All experiments are performed using a die-sinking EDM platform, model Sodick A30 Machine. The EDM process takes place in a 300 mm × 250 mm × 250 mm container as shown in Fig. 2. The stirring rotates at a speed of 90 r/min to maintain the uniformity of SiC powder in the dielectric fluid. A nozzle is used to pump liquid into the work zone to eject chips and maintain the stability of the discharge process. The task of the magnetic plate is to collect steel debris generated during machining to prevent them from re-entering the machining area. To determine MRR, a high-precision scale (precision of 0.001 g) is used to measure workpiece mass before and after each experiment repeats three times. The material of the electrode is copper, and Diel MS 7000 oil of Total company is utilized as dielectric fluid. The work material is 90CrSi tool steel with the hardness of 58–62 HRC. The employed SiC powder has a size of 500 nm. The statistical analysis is realized using the Minitab 18 software.

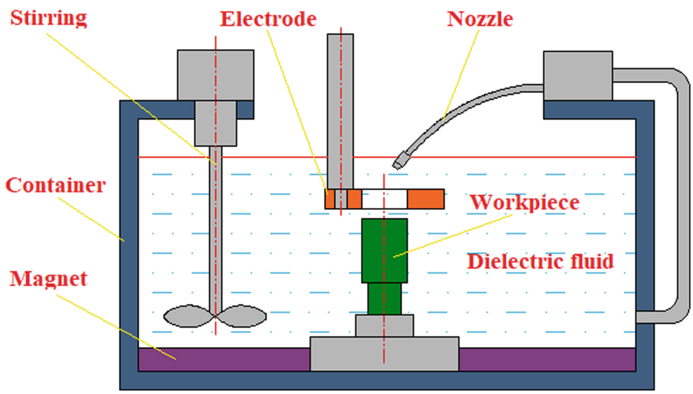

Fig. 2. Schematic diagram of the experiment

3 Results and Discussions

The results of the experiments and S/N ratio are shown in Table 2. The values of PMEDM parameters such as the C_p, T_{on}, T_{off}, IP, and SV are based on the arrangement of the L18 array. MRR values are obtained from 3 trials in each run. The means of MRR are distributed in the range from 0.001787 g/h (Run 7) to 0.452930 g/h (Run 10). The S/N is obtained by Minitab software.

Table 2. Results of experiments

Run	C_p	T_{on}	T_{off}	IP	SV	MRR [g/h]				
						Trial 1	Trial 2	Trial 3	Mean	S/N
1	0	6	14	4	3	0.01921	0.01925	0.01925	0.019241	−34.3156
2	0	10	21	8	4	0.01011	0.01012	0.01012	0.010121	−39.8957
3	0	14	30	12	5	0.24745	0.24651	0.24698	0.246981	−12.1468
4	2	6	14	8	4	0.00341	0.00339	0.00340	0.003404	−49.3611
5	2	10	21	12	5	0.33044	0.33016	0.33016	0.330254	−9.6230
6	2	14	30	4	3	0.03213	0.03213	0.03216	0.032142	−29.8586
7	2.5	6	21	4	5	0.00179	0.00178	0.00179	0.001787	−54.9584
8	2.5	10	30	8	3	0.03924	0.03916	0.03908	0.039163	−28.1426
9	2.5	14	14	12	4	0.33835	0.33835	0.33808	0.338263	−9.4149
10	3.5	6	30	12	4	0.45369	0.45233	0.45278	0.452930	−6.8794
11	3.5	10	14	4	5	0.05054	0.05058	0.05049	0.050535	−25.9281
12	3.5	14	21	8	3	0.00254	0.00253	0.00253	0.002536	−51.9155
13	4	10	30	4	4	0.32517	0.32488	0.32547	0.325175	−9.7577
14	4	14	14	8	5	0.00777	0.00775	0.00774	0.007752	−42.2115
15	4	6	30	8	5	0.00886	0.00883	0.00885	0.008847	−41.0643
16	4.5	10	14	12	3	0.31019	0.30989	0.31019	0.310090	−10.1703
17	4.5	14	21	4	4	0.00702	0.00701	0.00700	0.007013	−43.0820
18	4.5	14	30	8	3	0.00799	0.00798	0.00800	0.007989	−41.9507

Figure 3 shows the main effects plot for S/N ratio. As shown in the figure, the levels giving the maximum S/N values for each parameter include the fourth level of the powder concentration, the first level of the pulse-on-time, the third level of the pulse-off-time, the pulse current, and the server voltage. Therefore, the optimal input parameters for maximum MRR are the powder concentration of 3.5 g/l, the T_{on} of 6 µs, the pulse-off-time of 30 µs, the pulse current of 12 A, and the server voltage of 5 V.

Figure 4 shows the effect of nanopowder concentration on the MMR. An increase in powder concentration results in a growth in MRR. MRR expands by over 83% from 0.09211 g/h to 0.16867 g/h when SiC powder concentration rises from 0 g/l to 3.5 g/l. However, when the powder concentration is applied at a higher level, the MRR decreases. The increase in C_p which leads to the increase of MRR is explained by the fact that mixing SiC nanopowder into the dielectric widens the discharge gap and

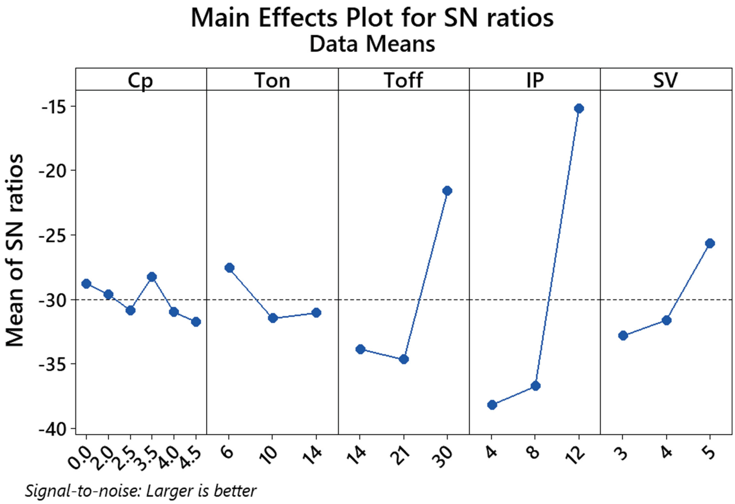

Fig. 3. Main effects for S/N ratio

increases the size of the plasma stream, which leads to an enhancement of MRR. However, when a powder concentration of more than 3.5 g/l is applied, the MRR decreases due to the short-circuit phenomenon causing the instability of the spark discharge.

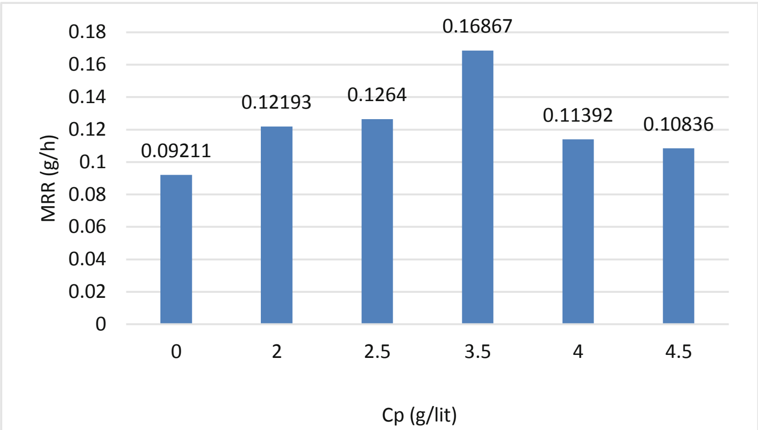

Fig. 4. Effect of nanopowder concentration on MRR

ANOVA for MRR is indicated in Table 3. It can be realized that the pulse current is the most prominent factor affecting MRR. The impact of the pulse current on MRR accounts for 42.61% of the total impact. The second strongest impact factor is pulse-off-time with 13.79% of the total effect. The effect of other factors is below 5% of the total effect.

Table 3. ANOVA for the MRR

Source	DF	Seq SS	AdjSS	AdjMS	F	P	%C
C_p	5	28.27	28.27	5.65	0.01	1.000	0.60
T_{on}	2	55.15	55.15	27.57	0.06	0.941	1.17
T_{off}	2	647.85	647.85	323.92	0.73	0.538	13.79
IP	2	2001.07	2001.07	1000.54	2.24	0.222	42.61
SV	2	178.01	178.01	89.01	0.20	0.827	3.79
Residual-error	4	1786.01	1786.01	446.50	–	–	–
Total	17	4696.36	–	–	–	–	–

The predicted average MMR ($\overline{MRR}_{OP}$) is determined by Eq. (2):

$$\overline{MRR}_{OP} = \overline{C}_{p4} + \overline{T}_{on1} + \overline{T}_{off3} + \overline{IP}_3 + \overline{SV}_3 - 4 * \overline{T}_{MRR} \quad (2)$$

Where $\overline{C}_{p4}$, $\overline{T}_{on1}$, $\overline{T}_{off3}$, $\overline{IP}_3$, $\overline{SV}_3$, $\overline{T}_{MRR}$ is the average MRR for C_p at level 4, T_{on} at level 1, T_{off} at level 3, IP at level 3, SV at level 3, and the average MMR, respectively

Based on Table 2, the values of parameters in Eq. (2) can be determined as the following:

$$\overline{C}_{p4} = 0,16867 g/h$$

$$\overline{T}_{on1} = 0,18544 g/h$$

$$\overline{T}_{off3} = 0,18151 g/h$$

$$\overline{IP}_3 = 0,28344 g/h$$

$$\overline{SV}_3 = 0,15808 g/h$$

$$\overline{T}_{MRR} = \frac{\sum_{i=1}^{18} MRR_I + \sum_{i=1}^{18} MRR_{II} + \sum_{i=1}^{18} MRR_{III}}{54} = 0,121901 g/h$$

By the Eq. (2):

$$\begin{aligned}\overline{MRR}_{OP} &= 0,16867 + 0,18544 + 0,18151 + 0,28344 + 0,15808 - 4 * 0,121901 \\ &= 0,48954 g/h\end{aligned}$$

A verification test is conducted with the optimal condition of PMEDM including the powder concentration of 3.5 g/l, the T_{on} of 6 µs the pulse-off-time of 30 µs, the pulse current of 12 A, and the server voltage of 5 V. The MMR obtained from the verification test is 0.656 µm. This result is 9.71% different from the predicted average MRR calculated by Eq. (2), which proves the reliability of the model developed by the research. In addition, MMR is greatly improved by the optimal PMEDM conditions when compared to machining by conventional EDM processes.

Figure 5 illustrates the normal probability plot of MMR. From the figure, MRR data description points are distributed nearby to the center line. It means that the input factors selected in the study have a statistically significant effect on the output response.

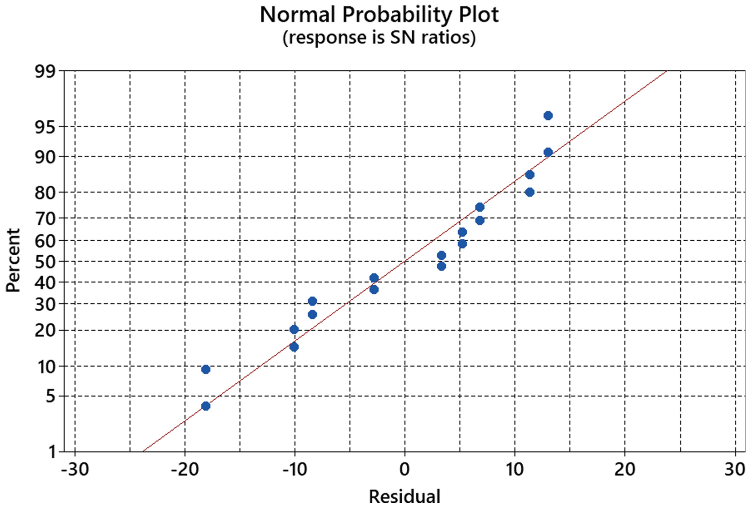

Fig. 5. Normal probability plot of MRR

4 Conclusion

In this study, Taguchi method and ANOVA were used to find the effect of powder mixed EDM parameters such as the powder concentration, Ton, the pulse-off-time, the pulse current, and the server voltage on MMR during machining of hardened 90CrSi steel. An optimal condition of the PMEDM process for maximizing MRR has been proposed. Some noteworthy conclusions of the study can be drawn as follows:

- Pulse current is the factor that has the most dominant impact on MMR followed by pulse-off-time. They contribute 42.61% and 13.79% to the total influence, respectively.
- The optimal condition of the PMEDM process for maximizing MRR includes the powder concentration of 3.5 g/l, the Ton of 6 µs the pulse-off-time of 30 µs, the pulse current of 12 A, and the server voltage of 5 V.
- The excellent effect of mixing SiC nanopowder on the dielectric fluid of the EDM process has been demonstrated. When applying the appropriate concentration of nanopowder (C_p = 3.5 g/l), MRR was enhanced by 83% compared to EDM process without mixing powder.

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