Application of the Multi-Criteria Decision Method to Find the Best Input Factors for Electrical Discharge Machining 90CrSi Tool Steel using Graphite Electrodes

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ABSTRACT

This paper examines the optimization of the Electrical Discharge Machining (EDM) process when machining cylindrical parts of 90CrSi tool steel using various graphite electrodes. A Multi-Criteria Decision Making (MCDM) approach, including the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), and Multi-Attributive Border Approximation Area Comparison (MABAC) was utilized to identify the optimal input factors that would achieve three machining objectives: minimizing Surface Roughness (SR) and Electrode Wear Rate (EWR) and maximizing Material Removal Rate (MRR). Criteria weights were calculated using the Method based on the Removal Effects of Criteria (MEREC). Additionally, three types of graphite electrodes (HK0, HK15, and HK20) and four process factors, such as Servo Voltage (SV), Input Current (IP), pulse on time (T_{on}), and pulse off time (T_{off}), were tested with experiments structured using a Taguchi L18 design and Minitab R19 software. The results indicate that the optimal EDM input parameters are: IP = 9.5 A, SV = 5 V, T_{on} = 8 µs, T_{off} = 8 µs, with the HK20 electrode balancing SR, EWR and MRR for enhanced machining performance.

Keywords-EDM; MCDM; TOPSIS; SAW; MABAC; SR; EWR; MRR; graphite electrodes

I. INTRODUCTION

EDM is a powerful non-traditional machining method widely utilized for generating complex shapes or removing materials from difficult-to-machine workpieces. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in various industries, including mold and die manufacturing, aerospace, and automotive. In addition, EDM does not make direct contact between the electrode and the workpiece eliminating mechanical stresses, chatter, and vibration problems during machining [1]. Since the EDM process is associated with the complex mechanisms and enormous technological parameters involved with it, the computation of parameters influence on quality indicators is tedious. MCDM techniques have to be performed since the process deals with multiple quality measures, such as MRR, TWR, and SR [2]. The dependence between input and output process parameters determines the exact choice of input parameters in any process.

Recent research has focused on optimizing critical EDM parameters, such as SR, Tool Wear Rate (TWR), and MRR, to improve machine efficiency and quality. Many of them have proved that input factors, like current, pulse-on time, pulse-off time, and voltage, influence significantly these indicators. Specifically, authors in [3] explored the EDM process of hybrid Aluminum Metal Matrix Composites (AMMC) and employed a multi-response optimization approach including the Entropy Weight Method (EWM), Taguchi, and the TOPSIS approaches to enhance SR, MRR, and TWR simultaneously. This study demonstrated that, based on the EWM- weighted priorities, a desirable balance of high MRR, minimal EWR, and acceptable SR could be achieved.

Authors in [4], examined the effects of machining parameters on EWR in cylindrical 90CrSi steel, determining optimal conditions through signal-to-noise ratio analysis to minimize the corresponding width. In [5], authors applied an Adaptive Neuro-Fuzzy Inference System (ANFIS) model for predicting MRR across different materials showing that ANFIS can provide high-accuracy predictions. Moreover, in the EDM of Ti-6AL-4V studied in [6], authors concluded that the TWR could be decreased remarkably through electrode coating, improving machining efficiency.

Despite these advancements in EDM, there is still a challenge of balancing multiple conflicting outputs, such as maximizing MRR while minimizing SR and TWR. The MCDM technique has proven to be effective in various fields for determining the most suitable response, including airport development [7], the best design parameters for a two-stage helical gearbox design [8], or the most appropriate input parameters for the milling process [9]. The utilization of MCDM in mechanical processing is increasingly prevalent. Authors in [10] applied four MCDM methods to identify the optimal input parameters for the turning process. In [11], authors utilized MCDM to address the Multi-Objective Optimization Problem (MOOP) in the surface grinding process, while authors in [12] employed the combination of two procedures for the selection of lathe machines.

II. METHODOLOGY

Three types of MCDM technique including SAW, TOPSIS, and MABAC methods were used to solve this problem, while the MEREC was applied to compute the criteria weights.

A. *Methods for solving MCDM*

1) *TOPSIS Method*

In this study, TOPSIS method was utilized to solve the MCDM problem. To use this technique efficiently, it is important to perform the following processes in a systematic order [13]:

- Make the decision-making matrix by:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \qquad (1)$$

where x_{mn} is the value of criterion n in variant m.

- Compute the normalized values k_{ij} by:

$$k_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad (2)$$

- Determine the weighted normalized decision matrix by:

$$l_{ij} = w_j \times k_{ij} \qquad (3)$$

where w_j is the weight of the j^{th} criterion.

- Calculate the best alternative A^+ and the worst alternative A^- by:

$$A^+ = \{l_1^+, l_2^+, \dots, l_j^+, \dots, l_n^+\} \qquad (4)$$

$$A^- = \{l_1^-, l_2^-, \dots, l_j^-, \dots, l_n^-\} \qquad (5)$$

Note that l_j^+ and l_j^- denote the best and worst values of the *j* criterion (*j*=1,2, ..., *n*).

- Find the better options D_i^+ and worse options D_i^- by:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(l_{ij} - l_j^+\right)^2} \qquad (6)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(l_{ij} - l_j^-\right)^2} \qquad (7)$$

where $i = 1, 2, \dots, m$ and and $j = 1, 2, \dots, n$.

- Determine the values R_i of each option by:

$$R_i = \frac{D_i^-}{D_i^- + D_i^+} \qquad (8)$$

where $0 \le R_i \le 1$.

- Rank the option's order by maximizing R_i.

2) *SAW Method*

The SAW technique is one of the most common MCDM methods and involves the following steps [14]:

- Make the first decision-making matrix:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \qquad (9)$$

- Determine the normalized matrix by:

$$n_{ij} = \frac{r_{ij}}{max r_{ij}} \qquad (10)$$

$$n_{ij} = \frac{min r_{ij}}{r_{ij}} \qquad (11)$$

where (10) is used for MRR and (11) for SR and EWR.

- Calculate the preference value for each alternative:

$$V_i = \sum_{j=1}^{n} w_j \cdot n_{ij} \qquad (12)$$

- Rank the order of options by maximizing V_i.

3) MABAC Method

The following steps employed for the MABAC method [15]:

- Build the initial decision-making matrix:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \qquad (13)$$

- Find the normalized values r_{ij}^* by:

$$r_{ij}^* = \frac{r_{ij} - r_i^-}{r_i^+ - r_i^-} \qquad (14)$$

$$r_{ij}^* = \frac{r_{ij} - r_i^+}{r_i^- - r_i^+} \qquad (15)$$

Equation (14) is used for MRR criteria, and (15) is used for the creation of SR and EWR.

- Compute the weighted matrix elements by:

$$v_{ij} = w_j + w_j \times r_{ij}^* \qquad (16)$$

- Calculate the border approximation area matrix:

$$g_j = \left(\prod_{i=1}^{m} v_{ij}\right)^{1/m} \qquad (17)$$

- Calculate the distance between the alternatives and the border approximation area by:

$$q_{ij} = v_{ij} - g_i \qquad (18)$$

- Determine the total distances of each option from the approximate border area:

$$S_i = \sum_{j=1}^{n} q_{ij}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. (19)

- Rank the alternatives by maximizing S_i.

B. Method to Find Creation Weights

The weights for the criteria in the MCDM analysis have been calculated utilizing the MEREC method. To carry out this approach, the stages that follow are executed [16]:

- Build the initial matrix using the identical methods from the first step of the TOPSIS technique.
- Compute the values of its elements utilizing the following outlined procedures:

For the MRR objective:

$$h_{ij} = \frac{\min x_{ij}}{x_{ij}} \qquad (20)$$

For the SR and EWR objectives:

$$h_{ij} = \frac{x_{ij}}{\max x_{ij}} \qquad (21)$$

- Find the effectiveness of the options S_i by:

$$S_i = \ln\left[1 + \left(\frac{1}{n}\sum_j \left|\ln(h_{ij})\right|\right)\right] \qquad (22)$$

- Determine the efficiency of the i^{th} option S'_{ij} by:

$$S'_{ij} = Ln\left[1 + \left(\frac{1}{n}\sum_{k,k\neq j} \left|\ln(h_{ij})\right|\right)\right] \qquad (23)$$

- Compute the removal effect of the j^{th} criterion E_j:

$$E_j = \sum_i \left|S'_{ij} - S_i\right| \qquad (23)$$

- Calculate the criteria's weight by:

$$w_j = \frac{E_j}{\sum_k E_k} \qquad (24)$$

III. EXPERIMENTAL WORK

This research investigated five process factors including SV, IP, T_{on}, T_{off}, and TOG as they constitute the main elements in the EDM process. Table I presents the input factors along with their corresponding levels. The values of the ranges of these survey parameters have been selected based on actual processing of cylindrical-shaped parts of 90CrSi at Thai Ha company (Thai Nguyen, Vietnam).

TABLE I. INPUT PARAMETERS

Input factors	**Units**	**Level**					
		1	**2**	**3**	**4**	**5**	**6**
IP	A	3.5	5.5	7.5	9.5	11.5	13.5
SV	V	4	5	6	-	-	-
T_{on}	µs	8	12	16	-	-	-
T_{off}	µs	8	12	16	-	-	-
TOG	-	HK0	HK15	HK20	-	-	-

The experiment was conducted and the data analysis was performed using the Taguchi method with Minitab R19 software. The L18 (6^1 + 3^4) design was also employed. The experimental setup, as illustrated in Figure 1, comprised the Sodick A30 EDM machine, a Mitutoyo 178-923-2A SJ-201 SR tester, samples created from 90CrSi tool steel, graphite electrodes, and the Diel MS 7000 dielectric solution. The requirements for the dimensions and tolerances of samples and electrodes are shown in Figure 2.

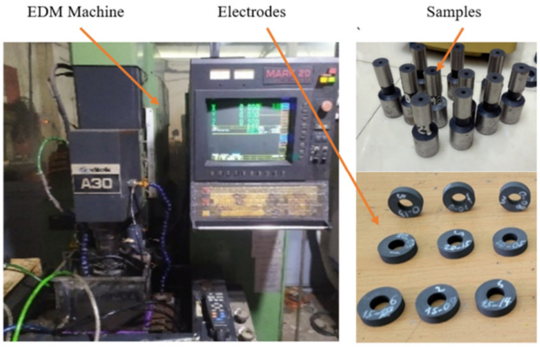

Fig. 1. Experimental setup.

The experiment was carried out in the following manner: The processing time for each sample was recorded during the experiment by the CNC machine's software. The masses of the electrodes and samples were measured before and after the experiment utilizing an electronic balance model WT3003NE, which offers a precision of 0.001 g. The SR of each sample was determined after each test run, while the EWR and MRR were computed utilizing the provided data in accordance with the stated formulas:

$$EWR = \sum_{i=1}^{n} \frac{m_{ebi} - m_{eai}}{t_{si}} \quad (26)$$

$$MRR = \sum_{i=1}^{n} \frac{m_{pbi} - m_{pai}}{t_{si}} \quad (25)$$

TABLE II. EXPERIMENTAL MATRIX AND OUTPUT RESULTS

IP (A)	SV (V)	T_{on} (µs)	T_{off} (µs)	TOG	SR (µm)	EWR (mg/min)	MRR (mg/min)
3.5	4	8	8	HK0	3.917	2.035	21.354
3.5	5	12	12	HK15	4.093	0.797	25.569
3.5	6	16	16	HK20	4.704	0.647	26.413
5.5	4	8	12	HK15	4.217	1.204	55.745
5.5	5	12	16	HK20	3.948	1.018	64.712
5.5	6	16	8	HK0	4.443	3.788	115.398
7.5	4	12	8	HK20	3.814	1.689	99.835
7.5	5	16	12	HK0	2.744	5.57	137.401
7.5	6	8	16	HK15	3.142	2.486	99.131
9.5	4	16	16	HK15	3.772	1.051	31.361
9.5	5	8	8	HK20	2.618	0.954	32.611
9.5	6	12	12	HK0	2.050	2.446	46.825
11.5	4	12	16	HK0	3.524	2.991	84.004
11.5	5	16	8	HK15	3.908	1.842	64.374
11.5	6	8	12	HK20	4.087	0.956	60.897
13.5	4	16	12	HK20	6.354	1.945	95.996
13.5	5	8	16	HK0	3.688	3.503	114.831
13.5	6	12	8	HK15	5.453	2.723	93.703

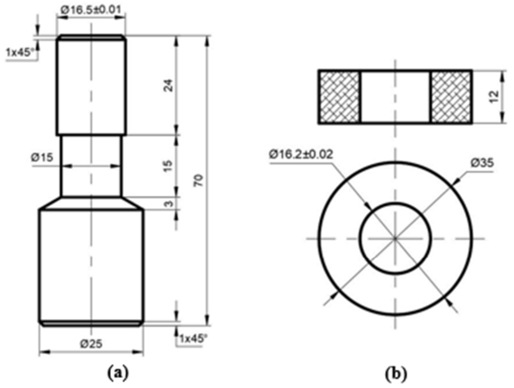

Fig. 2. Drawings of (a) samples and (b) electrodes.

IV. RESULTS AND DISCUSSION

Following the completion of the EDM experiment, SR, EWR, and MRR values, summarized in Table II, were used as input variables for solving the MCDM problem. Criteria weights for the SR, EWR, and MRR were determined through the MEREC technique, (20), (21), with resulting weights of 0.4201, 0.4679, and 0.1121, respectively.

The results and rankings for each MCDM technique are presented in Tables III-V. According to TOPSIS methodology (Table III), it was found that option 11 is the optimal choice achieving the highest value of R_i (R_i=0.8499). Similarly, the MABAC method, shown in Table IV, indicates option 11 as the best alternative with the highest S_i value of 0.2192. Finally, from the SAW method (Table V), it is noted that option 11 is the suitable one due to its highest V_i value (V_i=0.6728).

Figure 3 illustrates the ranking of options according to the three MCDM methods, based on the data presented in Tables III-V.

TABLE III. CALCULATED RESULTS AND RANKING OF OPTIONS IN TOPSIS METHOD

No.	k_{ij}			l_{ij}			D_i^+	D_i^-	R_i	Rank
	Ra	*EWR*	*MRR*	*Ra*	*EWR*	*MRR*				
1	0.2290	0.1969	0.0640	0.0962	0.0921	0.0072	0.0870	0.1709	0.6626	11
2	0.2392	0.0771	0.0766	0.1005	0.0361	0.0086	0.0630	0.2231	0.7798	5
3	0.2750	0.0626	0.0791	0.1155	0.0293	0.0089	0.0751	0.2265	0.7511	7
4	0.2465	0.1165	0.1670	0.1035	0.0545	0.0187	0.0649	0.2048	0.7593	6
5	0.2308	0.0985	0.1939	0.0969	0.0461	0.0217	0.0552	0.2149	0.7956	2
6	0.2597	0.3665	0.3457	0.1091	0.1715	0.0387	0.1540	0.0985	0.3901	17
7	0.2230	0.1634	0.2991	0.0937	0.0765	0.0335	0.0653	0.1883	0.7426	8
8	0.1604	0.5390	0.4116	0.0674	0.2522	0.0461	0.2235	0.0968	0.3022	18
9	0.1836	0.2405	0.2970	0.0771	0.1125	0.0333	0.0884	0.1625	0.6476	12
10	0.2205	0.1017	0.0940	0.0926	0.0476	0.0105	0.0582	0.2142	0.7863	4
11	0.1531	0.0923	0.0977	0.0643	0.0432	0.0109	0.0403	0.2283	0.8499	1
12	0.1198	0.2367	0.1403	0.0503	0.1107	0.0157	0.0869	0.1768	0.6703	10
13	0.2060	0.2894	0.2517	0.0865	0.1354	0.0282	0.1135	0.1375	0.5477	14
14	0.2284	0.1782	0.1929	0.0960	0.0834	0.0216	0.0749	0.1797	0.7059	9
15	0.2389	0.0925	0.1824	0.1004	0.0433	0.0204	0.0579	0.2166	0.7889	3
16	0.3714	0.1882	0.2876	0.1560	0.0881	0.0322	0.1217	0.1660	0.5770	13
17	0.2156	0.3390	0.3440	0.0906	0.1586	0.0385	0.1356	0.1184	0.4662	16
18	0.3187	0.2635	0.2807	0.1339	0.1233	0.0315	0.1266	0.1330	0.5123	15

TABLE IV. CALCULATED RESULTS AND RANKING OF OPTIONS IN MABAC METHOD

No.	g_{ij}			q_{ij}			S_i	Rank
	Ra	EWR	MRR	Ra	EWR	MRR		
1	0.6508	0.7882	0.1560	0.0072	0.0157	-0.0440	0.0212	13
2	0.6508	0.7882	0.1560	-0.0100	0.1333	-0.0399	0.0834	8
3	0.6508	0.7882	0.1560	-0.0696	0.1476	-0.0391	0.0388	11
4	0.6508	0.7882	0.1560	-0.0221	0.0946	-0.0108	0.0618	9
5	0.6508	0.7882	0.1560	0.0042	0.1123	-0.0021	0.1144	3
6	0.6508	0.7882	0.1560	-0.0441	-0.1509	0.0468	0.1482	16
7	0.6508	0.7882	0.1560	0.0172	0.0485	0.0318	0.0975	5
8	0.6508	0.7882	0.1560	0.1216	-0.3203	0.0681	0.1306	15
9	0.6508	0.7882	0.1560	0.0828	-0.0272	0.0311	0.0868	7
10	0.6508	0.7882	0.1560	0.0213	0.1092	-0.0343	0.0962	6
11	0.6508	0.7882	0.1560	0.1339	0.1184	-0.0331	0.2192	1
12	0.6508	0.7882	0.1560	0.1894	-0.0234	-0.0194	0.1466	2
13	0.6508	0.7882	0.1560	0.0455	-0.0752	0.0165	0.0132	12
14	0.6508	0.7882	0.1560	0.0080	0.0340	-0.0024	0.0396	10
15	0.6508	0.7882	0.1560	-0.0094	0.1182	-0.0058	0.1030	4
16	0.6508	0.7882	0.1560	-0.2307	0.0242	0.0281	0.1784	18
17	0.6508	0.7882	0.1560	0.0295	-0.1239	0.0463	0.0481	14
18	0.6508	0.7882	0.1560	-0.1427	-0.0497	0.0259	0.1665	17

TABLE V. CALCULATED RESULTS AND RANKING OF OPTIONS IN SAW METHOD

No.	n_{ij}			V_i	Rank
	Ra	EWR	MRR		
1	0.5234	0.3179	0.1554	0.3860	15
2	0.5009	0.8118	0.1861	0.6111	3
3	0.4358	1.0000	0.1922	0.6725	2
4	0.4862	0.5374	0.4057	0.5011	8
5	0.5193	0.6356	0.4710	0.5683	6
6	0.4614	0.1708	0.8399	0.3679	17
7	0.5374	0.3831	0.7266	0.4864	9
8	0.7470	0.1162	1.0000	0.4802	10
9	0.6525	0.2603	0.7215	0.4767	11
10	0.5435	0.6156	0.2282	0.5419	7
11	0.7829	0.6782	0.2373	0.6728	1
12	1.0000	0.2645	0.3408	0.5820	4
13	0.5817	0.2163	0.6114	0.4141	13
14	0.5246	0.3512	0.4685	0.4372	12
15	0.5016	0.6768	0.4432	0.5770	5
16	0.3226	0.3326	0.6987	0.3694	16
17	0.5558	0.1847	0.8357	0.4135	14
18	0.3760	0.2376	0.6820	0.3455	18

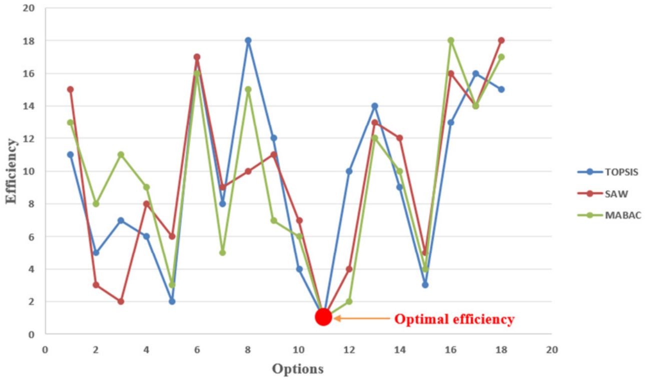

Fig. 3. Ranking of options by different MCDM methods.

The results from each method indicate that option 11 is the optimal one. This suggests that to get the minimum SR, minimum EWR, and maximum MRR simultaneously, the proposed EDM input parameters are IP = 9.5 A, SV = 5 V, T_{on} = 8 μs, T_{off} = 8 μs, using the HK20 electrode type.

V. CONCLUSIONS

This study presents an extensive analysis of identifying the optimal input factors in Electrical Discharge Machining (EDM) for cylindrically 90CrSi tool steel parts, utilizing various graphite electrodes. The Multi-Criteria Decision Making (MCDM) approach focused on three objectives: minimizing Surface Roughness (SR) and Electrode Wear Rate (EWR), and maximizing Material Removal Rate (MRR). Additionally, five factors including Servo Voltage (SV), Input Current (IP), pulse-on time (T_{on}), pulse-off time (T_{off}), and Types of Graphite (TOG), were examined using three types of graphite, HK0, HK15, and HK20, as electrode materials. The Taguchi method with an L18 ($6^1 + 3^4$) configuration, analyzed through Minitab R19, was employed to conduct the experiment. This investigation applied TOPSIS, SAW, and MABAC methods to address the MCDM challenges specific to this EDM setup, marking the first known application of these techniques. The application of the MCDM methods outlined does not influence the outcomes of identifying the optimal inputs showing the following values: IP = 9.5 A, SV = 5 V, T_{on} = 8 μs, T_{off} = 8 μs, electrode HK20.

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