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Micro-EDM, coated electrode, optimization

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THE OPTIMIZATION OF MICRO-EDM MACHINING PROCESS WHEN USING CARBON COATED MICRO ELECTRODE AS A TOOL

The amount of electrode wear in micro-EDM has a direct effect on the dimensional accuracy of the machined hole. Therefore, improving the corrosion resistance of electrodes in micro-EDM is still of great interest. The effective coating of thin film for the micro tool electrodes in the case of micro-EDM can lead to minimize the electrode wear which eventually improve the productivity and machining quality. In the present study, experiments were performed on micro-EDM using carbon coated tool electrode and optimized using Taguchi-Topsis to investigate optimum levels of Depth of cut (Z) and overcut (OVC). It was concluded that optimum conditions had improved significantly using carbon coated micro tool electrode. Optimal levels of technological parameters include V = 160 V, C = 10000 pF, RPM = 600 rpm, and Z_{opt} = 2.525 mm, OVC_{opt} = 65.257 μm. The quality of the machined surface with the coated electrode at optimal conditions is analysed and evaluated. The Topsis method is a suitable solution to this problem, and the steps to perform the calculation in this technique are simple.

1. INTRODUCTION

A crucial component in engineering sectors like aerospace and implant biomedicine is titanium alloy (Ti-6Al-4V). The most used technique for machining titanium alloys (Ti-6Al-4V) is EDM, specifically micro-EDM. In micro-EDM machining, productivity and dimensional accuracy are crucial quality factors technical specialists are very interested in the simultaneous development of these quality metrics. Coated electrode micro-EDM is a fairly new method, and it shows great promise for increasing micro-EDM machining efficiency. However, various materials have distinct impacts on the machining quality parameters when utilised to cover the electrode surface in micro-EDM. Currently, the number of studies of micro-EDM with coated electrode is very small. Therefore, research results in micro-EDM with coated electrode are published, and it will contribute to clarifying the influence of coating material on the micro-EDM machining process.

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Recently published research results in micro-EDM with coated electrode have shown that the coating material used in micro-EDM has a significant influence on the spark discharge process during material removal process. At the same time, the economic efficiency in using electrode materials has also been significantly improved. The Cu-coated Al electrode resulted in a reduction in the cost of the electrode material by approximately 2.85 times [1]. Even though, the cost of the electrode coating process also needs to be evaluated for the economic viability of this technique. MRR, TWR, HV and topography of machined surface in EDM with Cu coated electrode – MWCNT base is significantly improved [2]. Materials of coating alloys including Cu and MWCNT have been found on the machined surface layer, and this will affect the mechanical, physical and chemical properties of the workpiece surface. Cu electrode with Ag-coated material in EDM resulted in increased MRR, and decreased TWR and SR [3]. This contributes to improve machining performance in EDM. Comparing the performance of Cu and Ag electrode coating materials in micro-EDM machining with WC electrode has shown that the MRR of Cu coated WC is the largest, MRR of Ag coated WC electrode is the 2nd smallest, and the MRR and TWR of the WC electrode are the smallest [4]. The results were compared with the WC electrode, the TWR of the TiN coated electrode is reduced by 16.32% and the OVC of the coated electrode is reduced by 26%, and the machining efficiency of coated electrode is improved by approximately 18.9% [5]. The research articles were published on coated electrode which focused on comparing the efficiency of TiN, Ag and ZrN coated electrodes in micro-EDM showed that TiN coated electrode is the most suitable [6]. The EWR and OVC of the TiN coated electrode are the smallest, and they are the largest with the Ag coated electrode. The characteristics of melting, electrical and thermal conductivity of different materials, will affect the EDM process with coated electrodes differently [7]. The effective layer of Cu coating with Gr electrode by plating method, it provided to a improvement in the SR values of the machined surface, and this solution can be effectively used in finishing machining processes [8]. The values of TWR and overcut OVC in EDM with Al2O3 –TiO2 coated Cu electrode were significantly reduced, and the comparison between coated and uncoated electrodes showed that the TWR of the coated electrode decreased by 92% and the OVC of the coated electrode decreased by 62.5% [9]. The TWR of the Cu-ZrB2 coating electrode is much smaller than that of the uncoated electrode [10]. Parallel results were obtained with the ZniC coated Cu electrode in the EDM for Inconel alloy IN718 [11]. Results with the TiAlN coated electrode were compared and it was observed that the machining efficiency of TiN coated electrode was higher [12]. Surface quality after WEDM with Zinc coated electrode is significantly improved, the SR of the coated electrode is reduced by 15.01% compared to that of the uncoated electrode [13]. This shows the effectiveness of using coated electrode in improving the machined surface quality. Compared with uncoated electrode, Topography of machined surface with coated electrode is better [14]. The grain size in the coating layer significantly affects the crater size on the surface of the workpiece after EDM [15]. The optimal technological parameters in EDM using AlCrNi coated electrode were determined, and the TGRA method was used for multi objective optimization [16]. In addition, analysis of the surface layer after machining with AlCrNi, Cr and Ni coated electrodes was found in the machined surface layer. The optimal technological parameters in the micro-EDM using TiN coated electrode have been determined, and the dimensional accuracy of machining at optimal conditions has also been improved [17]. The surface quality at optimal conditions was evaluated by the analysis, and its results were good [18]. MRR and SR in EDM using coated electrode were decided simultaneously by TGRA [19]. However, the number of optimal research results in this area is still very small.

Determining the optimal technological parameters in the machining methods will significantly improve the machining efficiency, and this will be very meaningful for multi-objective optimization problems [20–21]. Taguchi method is very suitable for single-objective optimization problems, and multi-objective problems using this method will have a very complex computational process. Therefore, combining Taguchi with other multi-objective decision techniques has been studied and applied. In μ-EDM, several multi-objective decision techniques have been used [22]. TLBO algorithm is used to decide simultaneously drilling rate (DR) and tool wear rate (TWR) in micro-EDM, and the optimal result accuracy is good (max error = 4.81%) [23]. RSM is combined with ANN for multi-objective optimization in micro-EDM, the optimal result has a reasonable accuracy, and the maximum error of the optimal result is good [24]. Three quality parameters (MRR, TWR and SR) in EDM were simultaneously determined by Genetic Algorithm [25]. Optimal results have been shown, and EDM machined surface analysis at optimal conditions and its results is good. Optimal results in EDM with coated electrodes are also significantly improved with the calculation technique Taguchi-GRA [26]. RSM-Topsis are combined, and this combination is used for multi-objective decision in EDM, and the optimization results performed by RSM-TOPSIS are good [27]. TGRA technique has been applied in a number of studies on EDM and micro-EDM with coated electrode [28–30]. And the analysis of optimal machined surface quality after EDM with coated electrode is good [31–33]. The optimal mathematical results depend on technological parameters on the input of the research [34]. Research using multi-objective decision in micro-EDM is very necessary, it will promote the application of this technology in practice [35].

In this study, Simultaneous determination of Z and OVC in micro-EDM using carbon coated electrode for Ti-6Al-4V was performed. Optimal technological parameters were determined in this multi-objective problem, and the surface quality after the micro-EDM with the coated electrode at optimal conditions was analysed and evaluated. Topsis is combined with Taguchi to solve multi-objective problems.

2. MATERIALS AND DESIGN METHODOLOGY

The carbon coated WC electrode was used in the study, and the coating thickness of the electrode is approximately 10 microns. The results of EDX analysis shown in Fig. 1 show that the thin film coating consists of elements W, O, C, Co and Zn. The Chemical Vapor Deposition (CVD) was used for coating on Tungsten Carbide substrate up to 10 microns. The surface quality of the coated electrode is quite good, Fig. 2. The structural feature consists of small particles, and the sizes of the particles are quite similar, Fig. 3. The micro-EDM machine used in the experimental study is the Hyper 10 micro-EDM, and the rotating speed of the main shaft of the machine is in the range of 300-3000 rpm. The dielectric fluid is EDM oil, and the workpiece material is titanium alloy (Ti-6Al-4V). Ti-6Al-4V is one of the most widely used alloys because of its potential in maintaining excellent physical properties even at high temperatures. Some of the characteristics of these alloys include low weight associated with high strength, excellent resistance to fatigue and creep, good resistivity in corrosive environments, and biocompatibility. Ti-6Al-4V is used in various areas such as automotive, biomedical, aerospace, marine, and chemical processing industries. Due to the limitations of machining, this alloy (like low thermal conductivity and work hardening) with traditional machining, non-conventional machining methods, like laser beam machining, electrochemical methods, and EDM process was used for machining this type of material, machining of Ti-6Al-4V is the objective of research work. Quality indicators including *Z* and *OVC* were used in the study. The table of technological parameters in the micro-EDM selected in the study is as Table 1. Taguchi method is a widely used method in EDM and Micro-EDM studies because the number of experiments is very small, and the levels of the parameters are selected arbitrarily. Taguchi method was used to design the experiment in this study, and the experimental results are shown in Table 1. However, the multi-objective decision results determined by Taguchi are very complex, so combining Taguchi with other multi-objective techniques is the solution being used commonly. In this study, Taguchi-Topsis was used to decide simultaneously *Z* and *OVC* in micro-EDM using carbon coated electrode. The steps to combine Taguchi with Topsis are shown in Fig. 5. The TOPSIS methodology gives more practical models because the optimal indicators are allowed to trade off in this method, where good results received for one indicator would imply poor results in other indicators. The steps to perform the calculation in Topsis are shown in Fig. 6. The number of experiments performed in the Taguchi method is very small, so the optimal results in this study may not belong to the experiments investigated. Therefore, the optimal value needs to be determined by S/N factor analysis, and the value of S/N is determined as shown in Fig. 7.

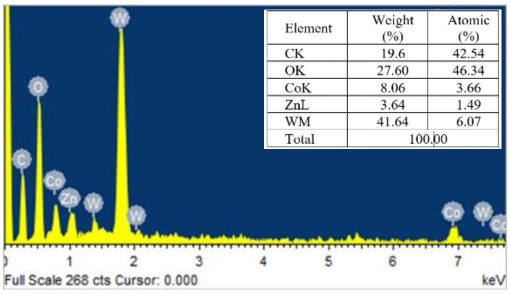


Fig. 1. EDX coating of electrode

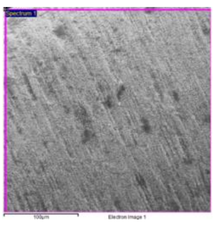


Fig. 2. Photograph of electrode surface

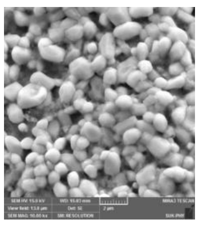
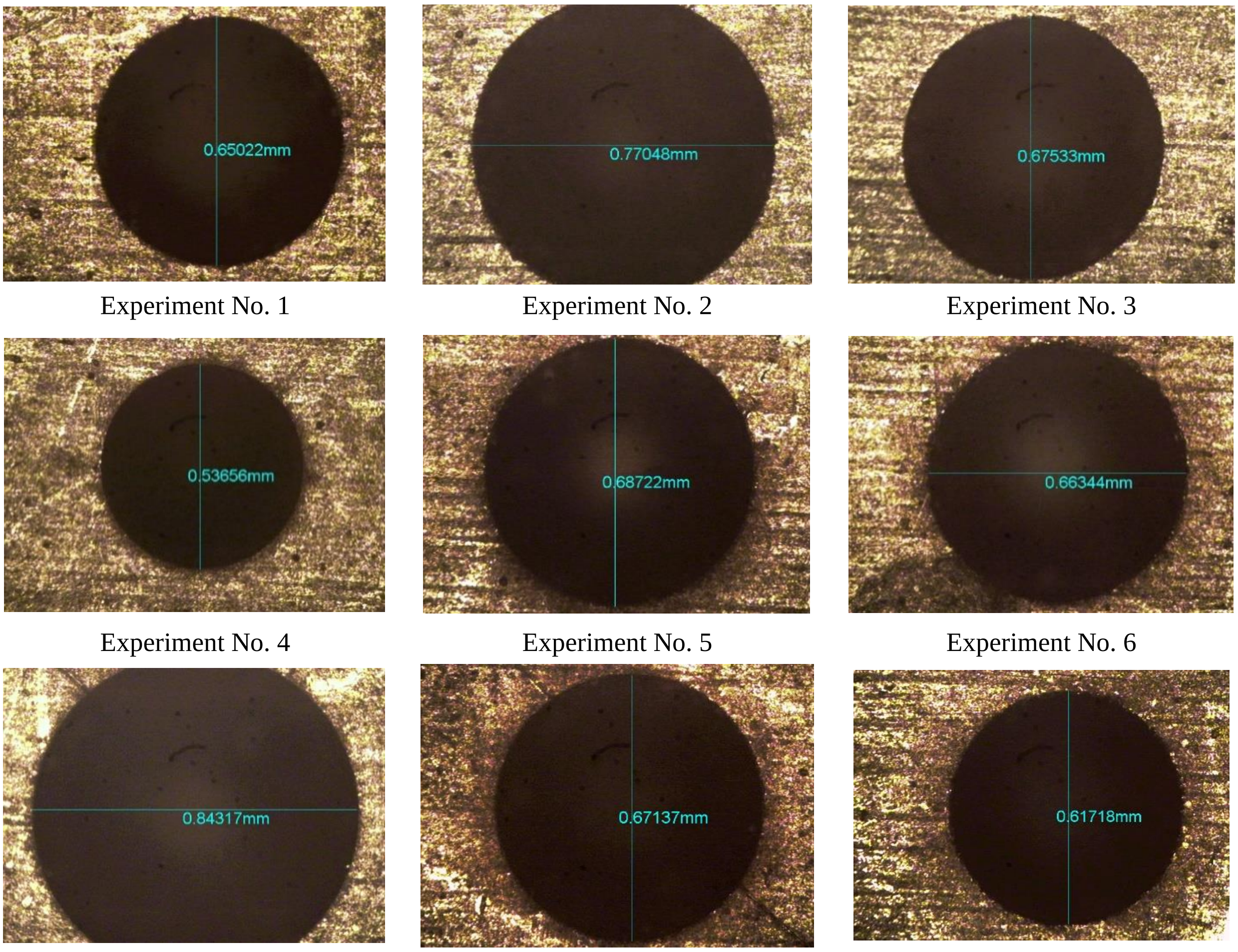


Fig. 3. Grain structure in the coating of electrode



Experiment No. 1 Experiment No. 2 Experiment No. 3

Experiment No. 4 Experiment No. 5 Experiment No. 6

Experiment No. 7 Experiment No. 8 Experiment No. 9

Fig. 4. Hole shape in micro-EDM using coated electrode

Table 1. Experimental Results with Carbon Coated Micro Tool Electrode

Ex. No.	Process parameters			Response variables			
				Coated electrode		Uncoated electrode	
	Voltage (V)	Capacitance (pF)	RPM (rpm)	*Z* (mm)	*OVC* (µm)	*Z* (mm)	*OVC* (µm)
1	120	100	200	0.6521	60.079	0.596	102.575
2	120	1000	400	1.232	23.945	1.162	30.344
3	120	10000	600	2.150	59.237	2.072	92.665
4	140	100	400	0.791	79.45	0.713	89.322
5	140	1000	600	1.399	41.297	1.394	90.02
6	140	10000	200	2.810	60.725	2.377	180.55
7	160	100	600	1.472	100.988	0.625	176.58
8	160	1000	200	1.307	67.213	1.179	90.685
9	160	10000	400	2.391	63.59	2.248	119.632

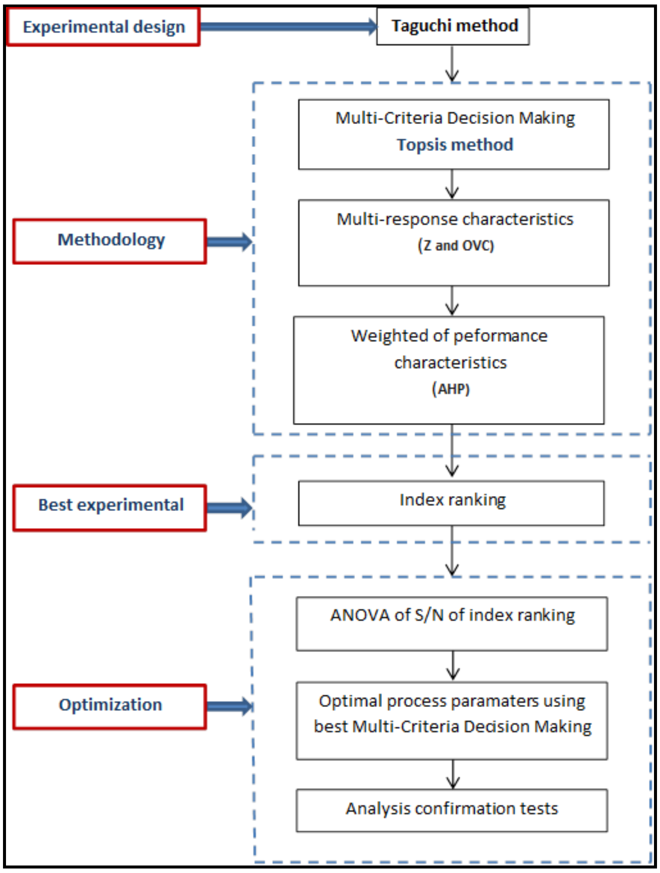


Fig. 5. Steps by TaguchiTopsis

Step 1: The decision matrix (X):

$$X=\begin{bmatrix} x_{11} & x_{12} & . & x_{1j} & x_{1n} \\ x_{21} & x_{22} & . & x_{2j} & x_{2n} \\ . & . & . & . & . \\ x_{i1} & x_{i2} & . & x_{ij} & x_{in} \\ . & . & . & . & . \\ x_{m1} & x_{m2} & . & x_{mj} & x_{mn} \end{bmatrix} \quad (1)$$

Step 2: The normalized decision matrix (X'):

$$x_{ij}^{'}=\frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^{2}}}$$

$$X^{'}=\begin{bmatrix} x_{11}^{'} & x_{12}^{'} & . & x_{1j}^{'} & x_{1n}^{'} \\ x_{21}^{'} & x_{22}^{'} & . & x_{2j}^{'} & x_{2n}^{'} \\ . & . & . & . & . \\ x_{i1}^{'} & x_{i2}^{'} & . & x_{ij}^{'} & x_{in}^{'} \\ . & . & . & . & . \\ x_{m1}^{'} & x_{m2}^{'} & . & x_{mj}^{'} & x_{mn}^{'} \end{bmatrix} \quad (2)$$

Step 3: The weighted normalized decision matrix (Y):

$$Y = w_j . x_{ij}^{'}$$

$$Y=\begin{bmatrix} y_{11} & y_{12} & . & y_{1j} & y_{1n} \\ y_{21} & y_{22} & . & y_{2j} & y_{2n} \\ . & . & . & . & . \\ y_{i1} & y_{i2} & . & y_{ij} & y_{in} \\ . & . & . & . & . \\ y_{m1} & y_{m2} & . & y_{mj} & y_{mn} \end{bmatrix} \quad (3)$$

Step 4: The ideal solutions (positive (A^+); negative (A^-)):

$$A^{+}=\left\{\left(\max_i y_{ij} \middle| \in J\right),\left(\min_i y_{ij} \middle| j \in J^{'} \middle| i=1,2,\ldots,m\right)\right\} \text{ (Best criteria)}$$

$$A^{+}=\left\{y_1^{+}, y_2^{+},\ldots, y_j^{+},\ldots, y_n^{+}\right\} \quad (4)$$

$$A^{-}=\left\{\left(\min_i y_{ij} \middle| \in J\right),\left(\max_i y_{ij} \middle| j \in J^{'} \middle| i=1,2,\ldots,m\right)\right\} \text{ (Worst criteria)}$$

$$A^{-}=\left\{y_1^{-}, y_2^{-},\ldots, y_j^{-},\ldots, y_n^{-}\right\} \quad (5)$$

Step 5: The separation measures (positive (S^+); negative (S^-)):

$$S_i^{+}=\sqrt{\sum_{j=1}^{n}\left(y_{ij}-y_j^{+}\right)^2} \quad i = 1, 2, \ldots, m \quad (6)$$

$$S_i^{-}=\sqrt{\sum_{j=1}^{n}\left(y_{ij}-y_j^{-}\right)^2} \quad i = 1, 2, \ldots, m \quad (7)$$

Step 6: The relative closeness to the ideal solution:

$$C_i^{*}=\frac{S_i^{-}}{S_i^{+}+S_i^{-}}, \quad i=1,2,\ldots,m; 0 \le C_i^{*} \le 1 \quad (8)$$

Step 7: Ranking.

Fig. 6. Calculation steps using Topsis

Smaller is better: S/N = -10 Log$_{10}$ [S] (9)

$$S=\frac{y_1^2+y_2^2+\ldots+y_n^2}{n}$$

S - The average squares of the measured values.

y_i - Value received by experiment (i = 1 ÷ n).

n - The number of experiments.

Larger is better: S/N = -10 Log$_{10}$ [L] (10)

$$L=\frac{\frac{1}{y_1^2}+\frac{1}{y_2^2}+\ldots+\frac{1}{y_n^2}}{n}$$

L- The average squared inverse of the measured values

Nominal value is the best: S/N = -10 Log$_{10}$ [N] (11)

$$N=\frac{(y_1-m)^2+(y_2-m)^2+\ldots+(y_n-m)^2}{n}$$

m - Value targets.

Fig. 7. Determine the value of Signal-to-noise (S/N) ratio

3. RESULTS AND DISCUSSION

3.1. INFLUENCE OF TOOL WITH AND WITHOUT COATING ON QUALITY MEASURES

The experimental investigation were done using EDM process with conventional WC micro tool electrode and carbon coated WC electrode. Table 1 shows the influence of coating performance measures on depth of cut, tool wear rate and overcut. The influence of coating on depth of cut was shown in Fig. 8. The material removal is directly proportional to the current flowing through the machining zone. Since the current is influenced by the electrical conductivity of tool electrode, the carbon coated electrode can produce higher depth of cut owing to the higher electrical conductivity of carbon coating. Hence the carbon coating electrode could produce larger depth of cut. The influence of coating on over cut was depicted in Fig. 9. The fine grain structure of the carbon coated WC tool electrode, which limits electron migration to the tool's edge, increasing the discharge current available at the frontal gap between electrode and specimens. Hence the carbon coated WC electrode could create lower over cut as compared with uncoated tool electrode. Hence it was found that carbon coated micro tool electrode could produce better performance measures in EDM.

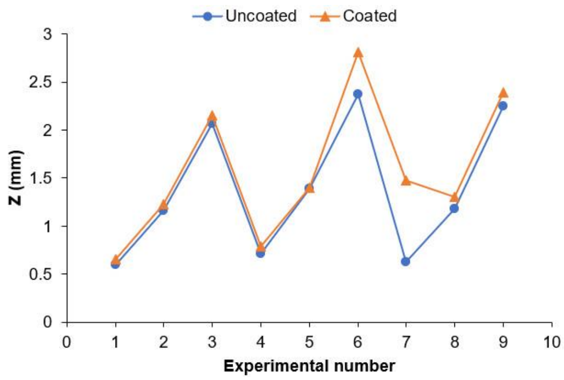


Fig. 8. Influence of coating on depth of cut

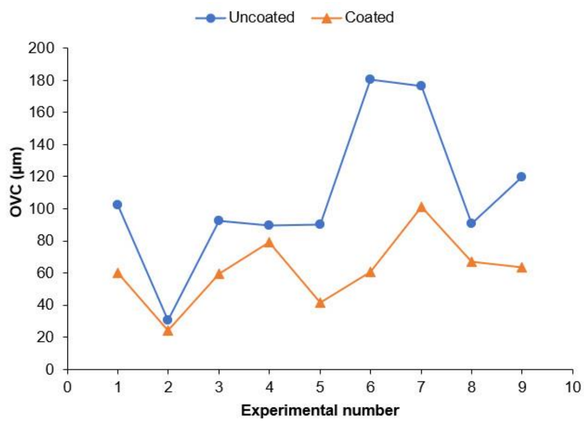


Fig. 9. Influence of coating on overcut

3.2. DETERMINATION OF THE BEST EXPERIMENTAL RESULTS BY TOPSIS METHOD

Step 1: Criteria matrix: Determined by formula (1), as follows:

$$X=\begin{bmatrix} Z_1 & OVC_1 \\ Z_2 & OVC_2 \\ & \\ & \\ Z_9 & OVC_9 \end{bmatrix}$$

Step 2: Normalize the Criteria's matrix: Determined by formula (2), Table 2:

Table 2. Normalized data

Exp. No	Voltage (V)	Capacitance (pF)	*RPM* (rpm)	Vector normalization	
				X_Z	X_{OVC}
1	120	100	200	0.1329	0.2675
2	120	1000	400	0.2512	0.1351
3	120	10000	600	0.4224	0.2638
4	140	100	400	0.1613	0.3977
5	140	1000	600	0.2852	0.1839
6	140	10000	200	0.4846	0.2704
7	160	100	600	0.3001	0.4497
8	160	1000	200	0.2665	0.2993
9	160	10000	400	0.4874	0.5327

Step 3: Criteria's weights: The Analytic Hierarchy Process (AHP) method is used in this study because of its simplicity and good accuracy. The following results W_Z = 0.667 and W_{OVC} = 0.333. The weight assignment with the quality criteria is determined by formula (3). Calculation results in Table 3.

Step 4: The best solution (A^+) and the worst solution (A^-): They are determined according to formulas (4) and (5), and the result is as follows

$A^+ = \{Z = 0.325; OVC = 0.045\}$ and $A^- = \{Z = 0.089; OVC = 0.117\}$.

Step 5: Calculation S_i^+ and S_i^-: They are determined according to formulas (5) and (6), and the results are as shown in Table 3.

Step 6: Calculation C*: These results in Table 3.

Step 7: Ranking: The ranking results are as shown in Table 3.

***** The best experiment: Analysis of the ranking results in Table 3 showed that

$$\boldsymbol{C_4^* < C_1^*} < C_7^* < C_8^* < C_2^* < C_5^* < C_9^* < C3^* < C_6^*.$$

This shows that the 6th exp. is the best. The best results of the multi-objective decision problem in this study are as follows V = 140V, C = 10000 pF and RPM = 200 rpm, and Z = 2.377 mm, OVC = 60.725 μm.

Table 3. Calculation results in Topsis and S/N ratio values

Exp. No	y'_Z	y'_{OVC}	y^+_Z	y^+_{OVC}	y^-_Z	y^-_{OVC}	S_i^+	S_i^-	C_i^*	Ranking	S/N ratio
1	0.089	0.089	–0.236	0.044	0.000	–0.088	0.2405	0.0883	0.269	8	0.269
2	0.168	0.045	–0.158	0.000	0.079	–0.132	0.1576	0.1541	0.494	5	0.494
3	0.282	0.088	–0.043	0.043	0.193	–0.090	0.0610	0.2128	0.777	2	0.777
4	0.108	0.132	–0.218	0.087	0.019	–0.045	0.2345	0.0487	0.172	9	0.172
5	0.190	0.061	–0.135	0.016	0.102	–0.116	0.1359	0.1543	0.532	4	0.532
6	**0.323**	**0.090**	**–0.002**	**0.045**	**0.235**	**–0.087**	**0.0451**	**0.2503**	**0.847**	**1**	0.847
7	0.200	0.150	–0.125	0.105	0.111	–0.028	0.1631	0.1149	0.413	7	0.413
8	0.178	0.100	–0.147	0.055	0.089	–0.078	0.1572	0.1182	0.429	6	0.429
9	0.325	0.177	0.000	0.132	0.236	0.000	0.1324	0.2365	0.641	3	0.641

3.3. DETERMINATION OF THE OPTIMAL RESULTS BY SIGNAL-TO-NOISE RATIO (S/N) ANALYSIS

The S/N value is determined by formula (12). Figure 10 has shown that the optimal technological parameters performed by Topsis include V = 160 V, C = 10000 pF, RPM = 400 rpm, and the optimal results are determined by Equation (11), Table 4. Compared with the calculated results of Z and OVC, the experimental results of Z and OVC have good accuracy.

$$(Z, OVC)_{opt} = V_3 + C_3 + RPM_3 - 3.\ \mathrm{T} \qquad (12)$$

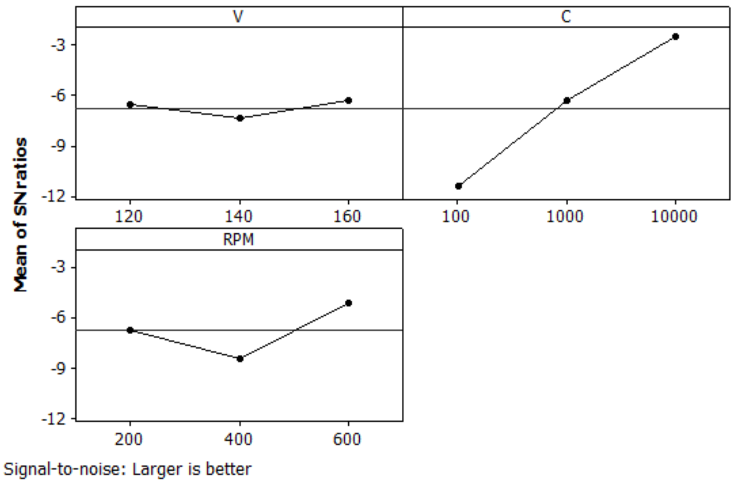


Fig. 10. Analysis of S/N of Topsis

Table 4. Multi-objective optimization results

Methods	Process parameters	Quality indicators	Results		Deviation (%)
			Cal.	Exp.	
Topsis	V =160 V, C = 10000 pF, RPM = 600 rpm	Z (mm)	2.407	2.525	4.90
		OVC (μm)	61.078	65.257	6.84

3.4. MACHINED SURFACE QUALITY AT OPTIMUM CONDITIONS

The dimensions of the machining hole after the micro-EDM using coated electrode at optimal conditions are shown in Fig. 11. The surface of the machined hole consists of adherent particles, Fig. 12. The cause may be that the chip particles have not been pushed out of the discharge gap between the electrode and the workpiece by the dielectric solution. Figure 13 shows that the shape and size of the adhesion particles are very variable, and they are distributed arbitrarily on the surface of the workpiece. This may be due to the random occurrence of sparks during the machining process, and the energy of each spark is not the same. Pores and cracks appear on the surface of the workpiece micro-EDM using coated in a significant amount, Fig. 14. These phenomena will significantly affect the roughness and working characteristics of the machined surface layer.

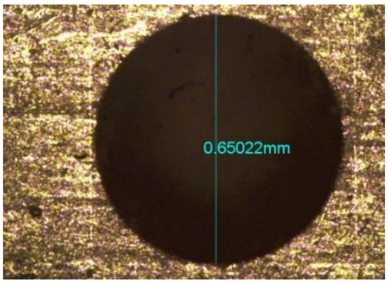


Fig. 11. Dimensions of the machining hole

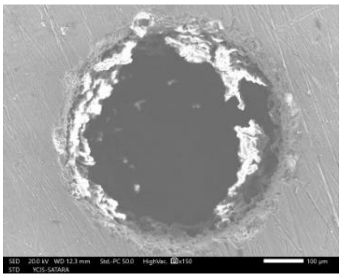


Fig. 12. SEM × 100 of machining hole

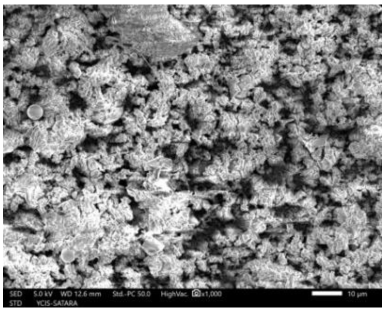


Fig. 13. Topography of machined surface

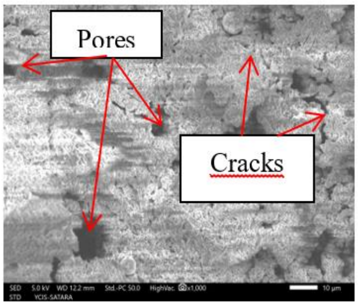


Fig. 14. Cracks on machined surface

4. CONCLUSIONS

The quality indicators in the micro-EDM using carbon coated WC electrode include *Z* and *OVC*, they were decided simultaneously by Taguchi-Topsis. The results of the study came to the following conclusions:

- The Carbon Coating has greatly improved the working efficiency of the aluminum electrode in the micro-EDM.
- Taguchi-Topsis were utilized to optimize the levels of process parameters and it was observed that Taguchi-Topsis is a very simple technique and easy to implement on any system.

- Compared with the good result calculated by the rating, the optimal result by S/N is better.
- The optimal technology parameters include V = 160 V, C = 10000 pF, RPM = 600 rpm and Z_{opt} = 2.525 mm, OVC_{opt} = 65.257 μm.
- Surface quality at optimum condition includes some defects such as microcracks, adherent particles and many subtle voids.
- Further studies are needed to clarify the effectiveness of using carbon coated electrodes in micro-EDM processing.

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