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MULTI-OBJECTIVES OPTIMIZATION OF MICRO-EDM PARAMETERS IN Ti-6Al-4V USING TOPSIS

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ABSTRACT:
In this paper, we performed trepanning of Ti-6Al-4V using copper rod and copper tube electrodes for micro-hole drilling, focusing on improving the machining efficiency and machined-hole quality in micro-electrical discharge machining (micro-EDM). However, optimizing micro-EDM parameters to enhance machining performance remains a key challenge. An L9 orthogonal array Taguchi design was employed to investigate the influence of voltage, current, pulse on-time and pulse off-time on critical machining outcomes: material removal rate (MRR), taper angle (TA), overcut at the top surface (OC_{top}), overcut at the bottom surface (OC_{bottom}), and circularity errors at both top (CE_{top}) and bottom surfaces (CE_{bottom}). Using technique for order of preference by similarity to ideal solution (TOPSIS) analysis, multi-objective superior and inferior solutions were identified for both copper rod and copper tube electrode shapes. For copper rod electrodes, the superior solution includes an MRR of 0.0004 mm^3/sec, TA of 0.1008°, OC_{top} of 0.0980 mm, OC_{bottom} of 0.1536 mm, CE_{top} of 0.0589 mm, and CE_{bottom} of 0.0656 mm. Meanwhile, the copper tube electrode's superior solution achieves an MRR of 0.0005 mm^3/sec, TA of 0.1823°, OC_{top} of 0.121 mm, OC_{bottom} of 0.2224 mm, CE_{top} of 0.0416 mm, and CE_{bottom} of 0.1837 mm. Furthermore, scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) analysis were conducted to examine surface characteristic under both superior and inferior machining conditions. The findings demonstrate that the use of copper tube electrode in micro-EDM significantly enhances machining efficiency, improves machined hole quality, and increases productivity while ensuring cost-effective small-hole drilling in hard-to-machine Ti-6Al-4V.
Keywords: micro-EDM, TOPSIS, copper rod, copper tube

INTRODUCTION:
Micro-hole drilling of Ti-6Al-4V plays a crucial role in precision applications across aerospace, biomedical, electronics, and microfluidic industries, where it is essential for turbine blade cooling, drug delivery systems, medical implants, and printed circuit board micro-sensors. A titanium alloy known for its exceptional strength-to-weight ratio, high-temperature resistance, biocompatibility, and superior corrosion resistance [1]. However, machining Ti-6Al-4V using conventional methods presents significant challenges due to its poor machinability, necessitating the adoption of non-traditional machining techniques such as micro-laser beam machining (micro-LBM), micro-electrochemical machining (micro-ECM), and micro-EDM [2-3]. Among these, micro-EDM has gained the most prominence in scientific research and industrial applications due to its superior capability in machining electrically conductive materials with high precision.
Despite its advantages, Micro-EDM faces several challenges in small-hole drilling, including electrode wear, accuracy limitations, and material removal efficiency. To address these issues, recent advancements in micro-EDM technology have focused on optimizing performance by developing new electrode materials, refining electrode geometries, achieving high aspect ratios in micro-holes,

and improving the microstructural integrity of machined surfaces. However, optimizing EDM process parameters to enhance machining efficiency and hole quality remains a significant challenge. While experimental studies provide valuable insights, they often fail to yield optimal solutions due to the complexity of machining variables. To overcome these limitations, optimization algorithms have been widely employed in manufacturing process optimization [4]. Notably, multi-objective optimization techniques, such as TOPSIS, particle swarm optimization (PSO), grey relational analysis (GRA), analytical hierarchy process (AHP), and genetic algorithms (GA), have demonstrated significant potential in improving machining efficiency and key performance characteristics [5-9]. Among these, TOPSIS is particularly recognized for its simplicity, robustness, and ability to handle complex engineering problems, making it a preferred approach for optimizing micro-EDM parameters [10-11].

LITERATURE:

This section provides a comprehensive review of previous studies on micro-EDM and related optimization techniques. Anthuvan and Krishnaraj (2020) performed a GRA to evaluate the MRR and tool wear rate (TWR) in electrical discharge machining of Ti-6Al-4V using copper electrodes with a 500 µm diameter. Their study explored various electrode coatings, including silver, nickel, zinc, and epoxy, to enhance MRR and minimize TWR. The results indicated that silver-coated electrodes achieved the highest MRR, while epoxy-coated electrodes exhibited the lowest TWR [12]. Kumar and Singh (2021) conducted blind hole drilling in Ti-6Al-4V using single and two-slotted rod electrodes. Their findings revealed that single-slotted electrodes resulted in higher aspect ratios and reduced taper angles compared to solid electrodes [13]. Chen et al. (2021) investigated the influence of various electrode materials, including copper-tungsten, on micro-EDM machining performance in Ti-6Al-4V alloy. Their study analyzed key parameters such as microstructure morphology, tool electrode wear, MRR, and recast layer thickness. The findings demonstrated that electrode material significantly affects machining efficiency and surface integrity [14]. Zou et al. (2023) explored uneven tool wear mechanisms in micro-EDM and found that using negatively polarized tool electrodes improved micro-hole accuracy [15]. Maddu et al. (2023) examined the EDM process for Ti-6Al-4V, focusing on critical parameters such as flushing pressure, pulse on-time, discharge current, and pulse off-time. Their research assessed the machining performance of copper, bronze, and brass electrodes, concluding that pulse on-time was the most significant factor influencing machining efficiency and material removal when using copper electrodes [16]. Pellegrini and Ravasio (2024) studied tool electrode wear in micro-EDM of Ti-6Al-4V, comparing cylindrical and tubular tungsten carbide electrodes. Their results indicated that tubular electrodes provided higher machining accuracy than cylindrical electrodes [17].Based on these studies, it is evident that electrode material, geometry, and polarity play crucial roles in determining machining performance.

Rex and Vijayan (2022) enhanced MRR, TWR, dimensional accuracy, and surface quality in the micro-EDM of Ti-6Al-4V by implementing TOPSIS as an optimization technique [18]. Similarly, Rajamanickam and Prasanna (2021) applied TOPSIS to optimize micro-hole drilling in both EDM and Powder-Mixed EDM (PMEDM) using copper and brass electrodes for machining Ti-6Al-4V [19]. In another study, Singh et al. (2022) utilized TOPSIS analysis in electrochemical discharge machining (ECDM) to evaluate the performance of micro-hole drilling in carbon fiber-reinforced polymer (CFRP) [20]. These studies collectively demonstrate that TOPSIS serves as an effective approach for optimizing EDM parameters, enabling cost-effective machining solutions by systematically analyzing their influence on key performance characteristics.

Considering these insights, a comparative study is conducted on both copper rod and copper tube electrodes in die-sinking EDM for small-hole drilling in Ti-6Al-4V. This eliminates the need for additional experimental setups while exploring the impact of electrode type on performance characteristics. The multi objective optimization through TOPSIS is executed to improve the MRR,

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taper angle, overcut at top surface, overcut at bottom surface, circularity at top and bottom surface in EDM of Ti-6Al-4V for small holes drilling. Additionally, the quality of the machined holes surface is investigated by the SEM and the EDS analysis. The methodology of EDM for small-hole drilling is illustrated in Figure 1.

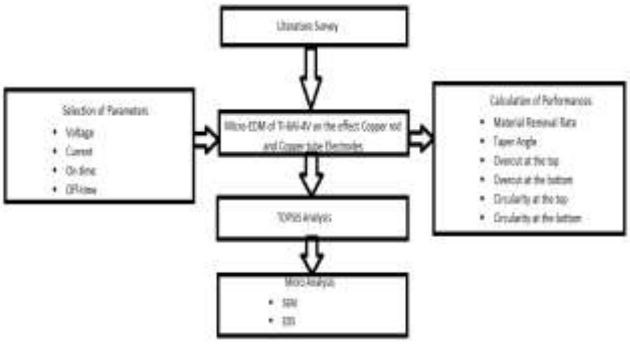

Figure 1: Methodology of EDM for small holes drilling

EXPERIMENTAL SETUP:

For the experiment, the ELTECH D-300 machine was used and it is revealed in the Table 1 with technical specifications. EDM for small holes drilling was planned using copper rod and copper tube electrodes having diameter of 300 µm. Ti-6Al-4V of 550 µm thickness was considered as workpiece due its unique properties and applications. The experimental factors —voltage, current, on-time and off-time— were selected at three levels, as indicated in the Table 2. The EDM experimental design followed an L9 orthogonal array, with the considering the selected factors and their levels, as summarized in the Table 3.

Table 1: Experimental setup with technical specifications

ELTECH D-300	Technical specifications
	Height = 2265 mm Width = 1280 mm Depth = 1350 mm Travel of the quill = 250 mm Depth of throat = 300 mm

Table 2: Experimental factors

Process parameters selected
Voltage : 40, 50 and 60 V
Current : 1, 1.5 and 2 A
On-time : 10, 20 and 30 µs
Off-Time : 5, 10 and 15 µs

The Ti-6Al-4V workpiece was connected to the negative terminal, while the electrode (copper rod/copper tube) was connected to the positive terminal of the EDM machine. Negative polarity was adopted to enhance the material removal volume of the workpiece. The machined holes top and bottom surfaces are measured using optical microscope. In EDM, rim of the machined hole is not being perfect circle. Since, average diameter of the machined holes at top and bottom surfaces is considered for the analysis. After small holes drilling operations, the performance characteristics such as material removal rate, taper angle, overcut at top surface, overcut at bottom surface, circularity at top surface and circularity at bottom surface on the effect of copper rod and copper tube electrodes are determined.

Table 3: Design of experimental layout (L9 Orthogonal array)

Sl. No.	Voltage (V)	Current (A)	On-time (μs)	Off-time (μs)
1	40	1	10	5
2	40	1.5	20	10
3	40	2	30	15
4	50	1	20	15
5	50	1.5	30	5
6	50	2	10	10
7	60	1	30	10
8	60	1.5	10	15
9	60	2	20	5

The MRR, OC_{top}, OC_{bottom} and TA were computed by using the equations 1-4. The circularity is defined as the distance between the minimum circumscribing circle diameter and the maximum inscribing circle diameter at the top surface/bottom surface. The circularity can be understood by seeing the Figure 2. Whereas, D_{top} is the diameter of hole at the top surface, D_{bottom} is the diameter of the hole at the bottom surface.

$$MRR = \frac{\pi * \text{thickness of the workpiece} * (Dtop^2 + dbottom^2 + Dtop * dbottom)}{12 * \text{time taken for machining}} \quad (1)$$

$$OC_{top} = D_{top} - D_{electrode} \quad (2)$$

$$OC_{bottom} = D_{bottom} - D_{electrode} \quad (3)$$

$$TA = \theta = \tan^{-1}\left\{\frac{(D_{top} - d_{bottom})}{2 \times \text{thickness of the workpiece}}\right\} \quad (4)$$

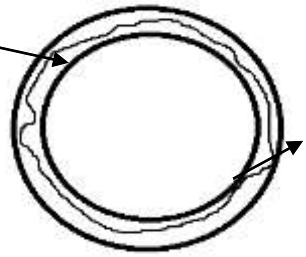

Figure 2: Circularity error measurement

Table 4 presents the experimental results of MRR, TA, OC_{top}, OC_{bottom}, CE_{top} and CE_{bottom} in the EDM of Ti-6Al-4V using copper rod electrodes, while Table 5 provides the corresponding data obtained with copper tube electrodes.

Table 4: Experimental values for EDM of Ti-6Al-4V using copper rod electrodes

Sl. No.	MRR (mm^3/sec)	TA (°)	OC_{top} (mm)	OC_{bottom} (mm)	CE_{top} (mm)	CE_{bottom} (mm)
1	0.0002	0.3741	0.0059	0.2095	0.0395	0.1856
2	0.0003	0.3371	0.0108	0.2036	0.0554	0.0311
3	0.0002	0.2269	0.0233	0.1503	0.0307	0.0672
4	0.0003	0.4186	0.0085	0.2030	0.0327	0.1760
5	0.0003	0.2207	0.0036	0.1270	0.0378	0.0456
6	0.0002	0.4021	0.0062	0.1655	0.0199	0.0927
7	0.0004	0.0590	0.1023	0.1347	0.0451	0.0428
8	0.0003	0.1399	0.0392	0.1167	0.1058	0.0548
9	0.0004	0.1008	0.0980	0.1536	0.0589	0.0656

Table 5: Experimental values for EDM of Ti-6Al-4V using copper tube electrodes

Sl. No.	MRR	TA	OC_{top}	OC_{bottom}	CE_{top}	CE_{bottom}

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	(mm^3/sec)	(°)	(mm)	(mm)	(mm)	(mm)
1	0.0004	0.3712	0.0110	0.2251	0.0317	0.2171
2	0.0004	0.1857	0.0364	0.1397	0.0259	0.0581
3	0.0004	0.1617	0.1198	0.2095	0.0409	0.1254
4	0.0004	0.0014	0.1294	0.1302	0.0246	0.0283
5	0.0003	0.1282	0.0580	0.1289	0.0364	0.0459
6	0.0005	0.1823	0.1210	0.2224	0.0416	0.1837
7	0.0006	0.2732	0.0985	0.2525	0.0475	0.0810
8	0.0005	0.0685	0.1519	0.1896	0.0397	0.0704
9	0.0005	0.0076	0.1333	0.1375	0.0526	0.0526

MULTI-CRITERIA DECISION MAKING USING TOPSIS ANALYSIS :

TOPSIS is simple, accurate and easy computation method widely used for involving any numbers of performance characteristics. Particularly, TOPSIS is logical descriptive process provides solutions for complex engineering problems towards close to their objectives. Experimental values of all the performance characteristics are arranged in the matrix form which is called decision matrix at the start of TOPSIS analysis and it can represented in equation 5. Step by step of TOPSIS analysis is shown in Figure 3 [21].

$$\text{Decision Matrix} = \begin{vmatrix} \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \\ \text{MRR} & \text{TA} & \text{OCtop} & \text{OCbottom} & \text{CEtop} & \text{CEbottom} \end{vmatrix} \quad (5)$$

1.1 Precision Agriculture

First step involves performing normalization using equation 6 to convert all the performance characteristics into a standardized format for computational analysis. Table 6 and Table 7 present the normalized values for copper rod and copper tube electrodes, respectively. These tables ensure consistent data representation, enabling an objective comparison of machining conditions.

$$c_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{y} b_{ij}^2}} \quad j=1,2,\ldots,x. \quad (6)$$

Where,

Cij: The normalized value of the performances.

b_{ij}: The original value of performances before normalization.

y: The total number of run in the experiments.

x: The total number of performances considered.

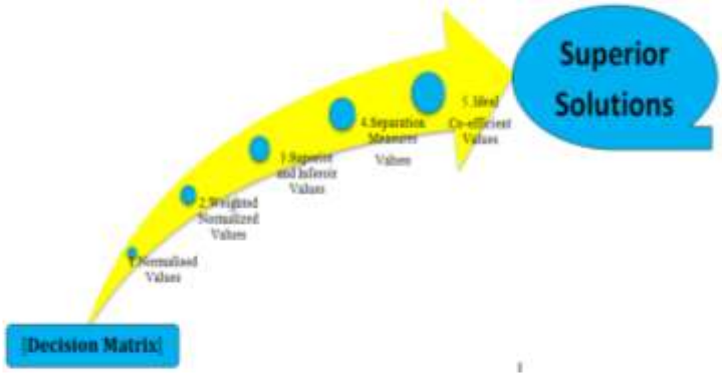

Figure 3: Step by step of TOPSIS analysis

Table 6: Normalized values using copper rod electrode

Sl. No.	MRR	TA	OC_{top}	OC_{bottom}	CE_{top}	CE_{bottom}
1	0.2514	0.4397	0.0397	0.4207	0.2489	0.6164
2	0.3214	0.3962	0.0722	0.4088	0.3494	0.1032
3	0.2327	0.2667	0.1555	0.3018	0.1935	0.2232
4	0.2921	0.4920	0.0564	0.4077	0.2063	0.5842
5	0.3126	0.2594	0.0244	0.2551	0.2382	0.1515
6	0.2717	0.4726	0.0415	0.3323	0.1256	0.3077
7	0.4356	0.0693	0.6831	0.2706	0.2842	0.1422
8	0.3373	0.1645	0.2618	0.2343	0.6669	0.1819
9	0.4680	0.1184	0.6545	0.3084	0.3715	0.2177

Table 7: Normalized values using copper tube electrode

Sl. No.	MRR	TA	OC_{top}	OC_{bottom}	CE_{top}	CE_{bottom}
1	0.4754	0.4362	0.0735	0.4520	0.1997	0.7207
2	0.4145	0.2182	0.2429	0.2805	0.1630	0.1929
3	0.4027	0.1900	0.8002	0.4207	0.2575	0.4165
4	0.4663	0.0016	0.8644	0.2614	0.1549	0.0941
5	0.3859	0.1507	0.3876	0.2589	0.2296	0.1523
6	0.5819	0.2143	0.8081	0.4466	0.2619	0.6099
7	0.6734	0.3211	0.6577	0.5071	0.2992	0.2690
8	0.5747	0.0805	1.0150	0.3808	0.2501	0.2337
9	0.5773	0.0089	0.8907	0.2761	0.3315	0.1746

1.2 Step: 2 Weighted Normalized values

In the second step, suitable weights are assigned to each performance characteristic to determine the weighted normalized values. Based on discussions with the expert, overcut is identified as a crucial performance characteristic from the end-user's perspective. Accordingly, little higher weights are assigned to overcut at the top and bottom surfaces compared to other characteristics. The assigned weights are as follows: MRR = 0.15, overcut at the top surface = 0.2, overcut at the bottom surface = 0.2, circularity at the top surface = 0.15, circularity at the bottom surface = 0.15, and taper angle = 0.15. The weighted normalization matrix values are calculated using equation 7, which incorporates the assigned weights into the normalized data to reflect the relative significance of each performance. The weighted normalized value for copper rod and copper tube electrodes are shown in the Table 8 and Table 9, respectively. These tables play a crucial role in facilitating an objective comparison of copper rod and copper tube electrodes performance, ultimately aiding in the selection of optimal machining parameters.

$$W = w_j c_{ij} \tag{7}$$

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Where,
W: The Weighted normalized value of the performances.
w_j: The weightage considered for the performances.

Table 8: Weighted normalized values using copper rod electrode

Sl. No.	MRR	TA	OC_{top}	OC_{bottom}	CE_{top}	CE_{bottom}
1	0.0377	0.0659	0.0079	0.0841	0.0373	0.0925
2	0.0482	0.0594	0.0144	0.0818	0.0524	0.0155
3	0.0349	0.0400	0.0311	0.0604	0.0290	0.0335
4	0.0438	0.0738	0.0113	0.0815	0.0309	0.0876
5	0.0469	0.0389	0.0049	0.0510	0.0357	0.0227
6	0.0408	0.0709	0.0083	0.0665	0.0188	0.0462
7	0.0653	0.0104	0.1366	0.0541	0.0426	0.0213
8	0.0506	0.0247	0.0524	0.0469	0.1000	0.0273
9	0.0702	0.0178	0.1309	0.0617	0.0557	0.0327

1.3 Step 3: Computations of superior and inferior values

The third step involves determining the superior and inferior values for each performance characteristic using Equation 8 and Equation 9. These values are crucial for evaluating the relative performance of the machining parameters. The computed superior and inferior values for each performance characteristic of copper rod and copper tube electrodes are presented in Table 10.

$$W^{+} = (W_1^{+} W_2^{+}, \ldots . W_x^{+}) \text{Maximum values} \quad (8)$$

$$W^{-} = (W_1^{-} W_2^{-}, \ldots . W_x^{-}) \text{Minimum values} \quad (9)$$

Where,
W^{+}: The Superior (maximum) value.
W^{-}: The Inferior (minimum) value.
W_1^{+} or W_1^{-} : Weighted normalized values for experiment 1.
W_x^{+} or W_x^{-} : Weighted normalized values for experiment x.

Table 9: Weighted normalized values using copper tube electrode

Sl. No.	MRR	TA	OC_{top}	OC_{bottom}	CE_{top}	CE_{bottom}
1	0.0713	0.0654	0.0147	0.0904	0.0300	0.1081
2	0.0622	0.0327	0.0486	0.0561	0.0244	0.0289
3	0.0604	0.0285	0.1600	0.0841	0.0386	0.0625
4	0.0699	0.0002	0.1729	0.0523	0.0232	0.0141
5	0.0579	0.0226	0.0775	0.0518	0.0344	0.0228
6	0.0873	0.0321	0.1616	0.0893	0.0393	0.0915
7	0.1010	0.0482	0.1315	0.1014	0.0449	0.0403
8	0.0862	0.0121	0.2030	0.0762	0.0375	0.0351
9	0.0866	0.0013	0.1781	0.0552	0.0497	0.0262

1.4 Step 4: Computations of separation measures

The separation measure equations, given in Equation (10) and Equation (11), are used to compute the superior and inferior measures, respectively.

$$SM_i^{+} = \sqrt{\sum_{j=1}^{x} \left(W_{ij} - W_J^{+}\right)^2} \quad (10)$$

$$SM_i^{-} = \sqrt{\sum_{j=1}^{x} \left(W_{ij} - W_J^{-}\right)^2} \text{ , where i=1,2,.....y} \quad (11)$$

Where,
SM_i^{+}: The superior separation measure for experiment i.
SM_i^{-}: The inferior separation measure for experiment i.

W_{ij} : The weighted normalized value for parameter j in experiment i.

Table 10: Superior and inferior values using copper rod and copper tube electrodes

Performance characteristics	Copper rod		Copper tube	
	Superior	Inferior	Superior	Inferior
Material removal rate	0.0702	0.0349	0.1010	0.0579
Taper angle	0.0104	0.0738	0.0002	0.0654
Overcut at top surface	0.0049	0.1366	0.0147	0.2030
Overcut at bottom surface	0.0469	0.0841	0.0518	0.1014
Circularity at top surface	0.0188	0.1000	0.0232	0.0497
Circularity at bottom surface	0.0155	0.0925	0.0141	0.1081

1.5 Step 5: Computation of Ideal coefficient

Ideal co-efficient of all experimental run, relative to the superior ideal solution, is computed using equation 12. It is stated as

$$\text{Ideal Co} - \text{efficient (IC)} = \frac{SM_i^-}{(SM_i^+ + SM_i^-)} \quad (12)$$

Finally, experimental runs are ranked according to the ideal coefficient values.

RESULTS AND DISCUSSION:

The multi-objective optimization study using TOPSIS is conducted to evaluate various performance characteristics, identifying solutions that are closest to the ideal and farthest from the ideal. The separation measure values, ideal coefficient values and rankings for copper rod and copper tube electrodes are presented in Table 11 and Table 12, respectively. Figure 4 presents a comparative study on the influence of copper rod and copper tube electrodes on the ideal coefficient values during the micro-EDM of Ti-6Al-4V, analyzed using TOPSIS. This method is employed to consolidate all six performance characteristics into a single numerical value, known as the ideal coefficient, where a higher value indicates better performance (from Table 6 to Table 12).

The results show that experimental run 9 achieved the highest ideal coefficient value of 0.5898 among the trials using copper rod electrodes (Table 11), demonstrating superior performance characteristics. Similarly, for copper tube electrodes, experimental run 6 exhibited the multi-objectives optimal machining parameters setting, attaining a maximum ideal coefficient value of 0.7033 (Table 12). Conversely, the lowest ideal coefficient value for copper rod electrodes was 0.1748 in experimental run 5, while for copper tube electrodes, the lowest value was 0.2933 in experimental run 2. Notably, the ideal coefficient values for copper tube electrodes were consistently higher than those for copper rod electrodes. These findings, as visualized in Figure 4, highlight the performance differences between copper rod and copper tube electrodes in the micro-EDM of Ti-6Al-4V for small-hole drilling.

Table 11: Separation measures, ideal coefficient and rank values of copper rod electrode

Sl.No.	Separation measures		Ideal coefficient	Rank
	Superior	Inferior		
1	0.1470	0.1037	0.4137	5
2	0.1543	0.0708	0.3146	6
3	0.1504	0.0466	0.2367	8
4	0.1456	0.1034	0.4153	4
5	0.1709	0.0362	0.1748	9
6	0.1624	0.0709	0.3039	7
7	0.1153	0.1376	0.5441	2
8	0.1246	0.0971	0.4380	3

9	0.0960	0.1380	0.5898	1

Table 12: Separation measures, ideal coefficient and rank values of copper tube electrode

Sl. No.	Separation measures		Ideal coefficient	Rank
	Superior	Inferior		
1	0.1419	0.1227	0.4637	7
2	0.1415	0.0588	0.2933	9
3	0.0858	0.1704	0.6651	2
4	0.1406	0.1721	0.5503	6
5	0.1283	0.0792	0.3818	8
6	0.0798	0.1892	0.7033	1
7	0.0877	0.1616	0.6483	3
8	0.1255	0.2085	0.6243	4
9	0.1225	0.1842	0.6006	5

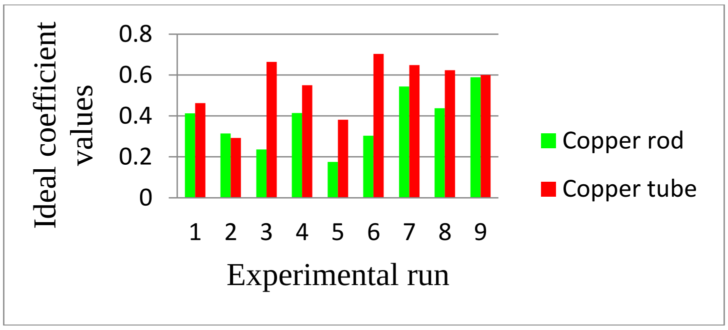

Figure 4: Comparative analysis of IC values

1.6 Micro analysis

After carrying out the computational analysis (TOPSIS), the workpiece surfaces were examined using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) for micro-analysis to confirm the results obtained. The machined-hole profiles were analyzed under superior and inferior machining settings of copper rod and copper tube electrodes in SEM. EDS analysis identified various metal elements near the rim of the machined-hole surfaces.Figures 5–8 represent SEM microscopic views of machined-hole in the EDM of Ti-6Al-4V under superior and inferior machining conditions using copper rod and copper tube electrodes. The analysis reveals that holes machined with the copper tube electrode exhibit a more uniform circular profile and improved surface smoothness. Additionally, the rim of the machined holes closely aligns with the electrode's diameter when using the copper tube electrode, in contrast to the copper rod electrode.

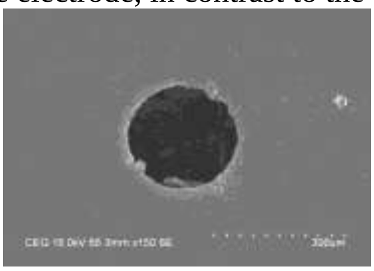

Figure 5: Superior settings of copper rod

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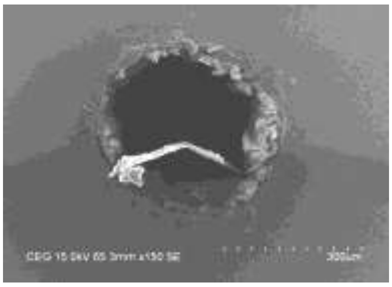

Figure 6: Inferior settings of copper rod

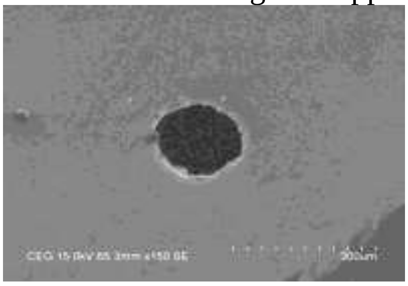

Figure 7: Superior settings of copper tube

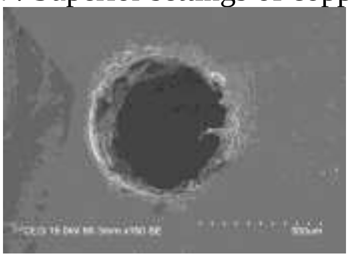

Figure 8: Inferior settings of copper tube

EDM analysis has been conducted on the superior and inferior machining parameters settings in EDM of Ti-6Al-4V while using copper rod and copper tube electrodes nearer to the rim of the machined holes surface. The analysis indicates a significant amount of eroded material embedded on the rim of the machined holes. Figures 9–10 highlight the EDS images for copper rod electrodes, while Figures 11–12 display the EDS images for copper tube electrodes under superior and inferior machining settings. These images confirm the chemical composition of the elements present, validating the material composition of both the workpiece (Ti-6Al-4V) and the electrode (copper) material.

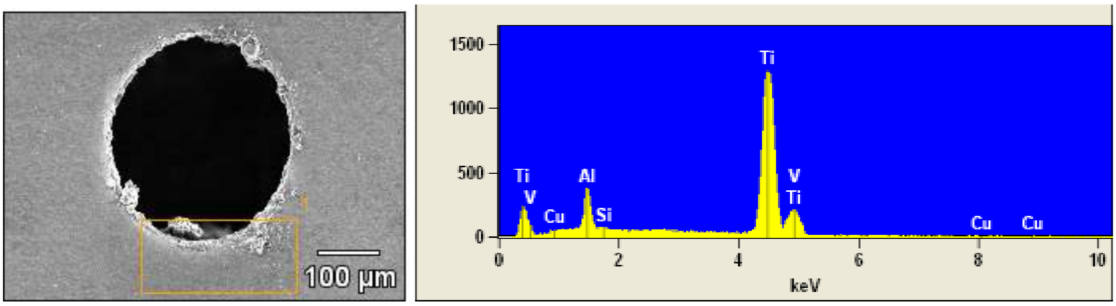

Figure 9: Superior EDS image of copper rod

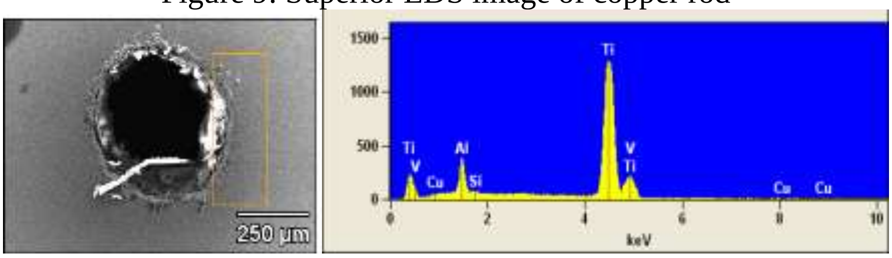

Figure 10: Inferior EDS image of copper rod

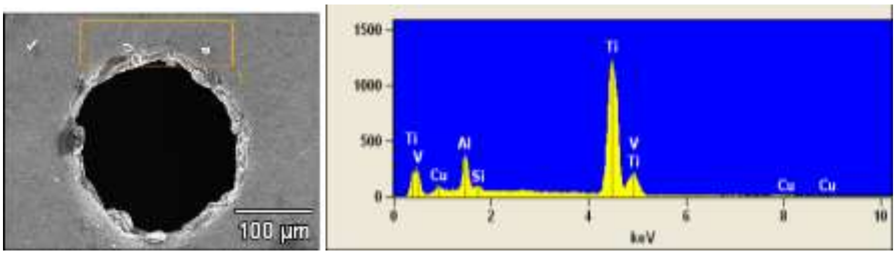

Figure 11: Superior EDS image of copper tube

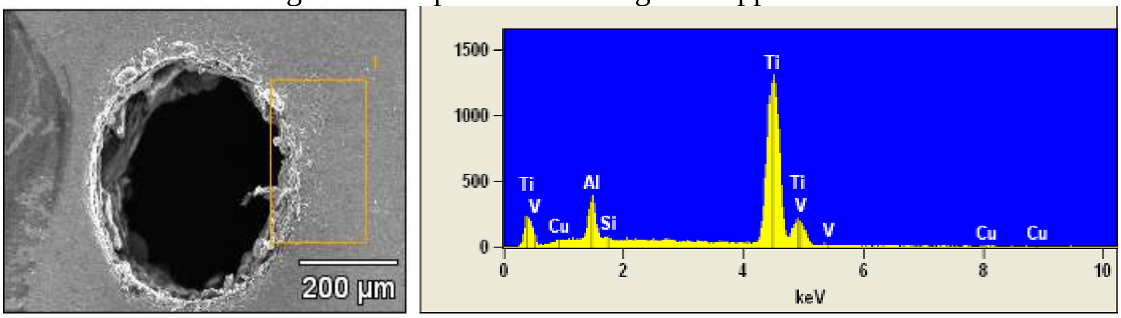

Figure 12: Inferior SEM image of copper tube

CONCLUSION :

This research paper investigates small-hole drilling in EDM of Ti-6Al-4V using two different types of electrodes: copper rod and copper tube, both with a diameter of 300 µm. Multi-objective optimization using the TOPSIS method was applied to determine the multi-objective optimal machining settings for superior performance characteristics. The TOPSIS analysis has identified voltage of 60 V, current of 2 A, on-time of 20 µs and off-time of 5 µs as the multi-objective optimal machining settings for copper rod electrode. The TOPSIS analysis has also identified voltage of 50 V, current of 2 A, on-time of 10 µs and off-time of 10 µs as the superior combination factors for copper tube electrode. These findings provide a systematic approach to identifying the optimal parameter settings for improved performance characteristics such as MRR, TA, OCtop, OCbottom, CEtop and CEbottom while machining Ti-6Al-4V alloy using copper rod and copper tube electrodes. Micro-analysis reveals that holes machined with the copper tube electrode exhibit a more uniform circular profile, improved surface smoothness and a rim closely aligning with the electrode’s diameter, unlike those machined with the copper rod electrode.EDS analysis confirmed the elemental composition of the workpiece (Ti-6Al-4V) and electrode (copper) on the rim profile of the machined hole, validating the results and ensuring material integrity under varying machining conditions.

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