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RESEARCH

Optimizing Technological Parameters in Electrical Discharge Machining with Graphene-Coated Aluminum Electrodes for Enhanced Machining of Titanium Alloy: A Taguchi-TOPSIS Approach

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ABSTRACT

Electrical Discharge Machining (EDM) employing coated electrodes represents a relatively unexplored research avenue, with limited published findings to date. The choice of coating material significantly influences the EDM machining process, directly impacting the adjustment of technological parameters. Consequently, an in-depth investigation into the optimization of technological parameters for EDM with coated electrodes is imperative, aiming to propel the practical application of this innovative technique. This study focuses on determining the technological parameters for EDM utilizing an aluminum (Al) electrode coated with graphene for machining titanium alloy (Ti-6Al-4V). The research addresses a multi-objective optimization problem, with Material Removal Rate (MRR) and Tool Wear Rate (TWR) serving as key quality indicators. The integration of the Taguchi method with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is employed to address the multi-objective nature of the optimization challenge. The obtained results pinpoint optimal process parameters as U = 55 V, I = 5 A, and Ton = 1500 µs, resulting in an MRR of 6.57 mg/min. An in-depth analysis and evaluation of the machined surface quality with the coated electrode under optimal conditions are conducted. The TOPSIS method emerges as a fitting solution for this multi-objective optimization problem, offering simplicity in its computational steps.

1. INTRODUCTION

Electrical Discharge Machining (EDM) stands as a pivotal method in fabricating intricate surfaces with challenging-to-machine materials [1]. Nevertheless, the production cost of electrodes remains a substantial component of overall processing expenses, impeding the cost-effectiveness of this technology. The continuous wear of electrodes during machining poses challenges to accuracy and cost efficiency [2]. Consequently, enhancing electrode longevity emerges as a critical quality indicator in EDM, demanding rigorous research endeavors.

Recent research in EDM has explored diverse avenues such as optimizing technological parameters, employing novel electrode materials, utilizing innovative technological solutions (e.g., integrated vibration or powder in dielectric solution), and incorporating coated electrodes. Among these, EDM with coated electrodes represents a novel technical solution garnering significant attention from experts in the field. The choice of coating material profoundly influences the adjustment parameters of the EDM machine, necessitating comprehensive investigations into optimizing technological parameters in this context.

Although research outcomes in EDM with coated electrodes are limited, existing studies underscore the substantial improvements achievable with suitable coating materials. Notably, the use of coated electrodes has demonstrated a remarkable reduction in electrode material costs by approximately 2.85 times [3]. The dimensional accuracy achieved through micro-Electrical Discharge Machining (μ-EDM) utilizing a Cu-ZrB2 coated electrode surpasses that attained with a conventional Cu electrode. Enhanced quality indicators in EDM, manifested through improved efficiency, have been reported with coated electrodes [4]. Studies employing Ag coated electrodes have shown marked improvements in the machined surface layer composition, contributing to heightened product surface quality [5].

Comparative analyses across different coating materials, such as Cu and Ag, have revealed variations in Material Removal Rate (MRR) and machining efficiency [6]. Additionally, investigations into electrode coatings, including TiN, Ag, and ZrN, have indicated TiN as the most suitable material for EDM [7,8]. Unique coating methods, such as Cu coating with Gr electrode by plating, have demonstrated effective utilization in finishing machining processes, particularly in enhancing Surface Roughness (SR) values [9].

In comparison to conventional copper electrodes, the utilization of copper-based multi-walled carbon nanotube (MWCNT) composite coated electrodes in Electrical Discharge Machining (EDM) yields noteworthy advancements in Tool Wear Rate (TWR) and Material Removal Rate (MRR), with a remarkable 99.52% increase in MRR and a significant 57.11% reduction in TWR [11]. Additionally, investigations into EDM utilizing nickel alloy-coated copper electrodes have been scrutinized, revealing that while the MRR of the coated electrode is diminished compared to bare copper, the surface quality is substantially enhanced [12]. Furthermore, experimentation with aluminum oxide-titanium dioxide coated copper electrodes in EDM applications for Ti-6Al-4V demonstrates reductions in TWR and overcut by 92% and 62.5%, respectively, highlighting the efficacy of coated electrodes in EDM processes [13].

Moreover, the economic viability of EDM utilizing coated Ak12 electrodes has been notably enhanced, with an approximate 35% improvement over the conventional copper electrode approach [14]. Additionally, the surface quality post-machining following micro-EDM leveraging boron-coated chemical vapor deposition (CVD) diamond electrodes exhibits significant enhancement [15]. This observed improvement can be attributed to the nuanced physicochemical properties and superior thermal conductivity inherent in the coatings, impacting both the spark generation process and the wear resistance characteristics of the electrode.

These findings underscore the importance of exploring various coating materials, such as copper and silver, in EDM processes, as they offer substantial quantitative benefits in terms of tool performance and material removal rates. However, despite these advancements, there exists a notable gap in understanding the optimal coating material and its precise influence on EDM responses, suggesting a promising avenue for further research.

At the forefront of this research lies the determination of optimal technological parameters in Electrical Discharge Machining (EDM) through the utilization of AlCrNi coated electrodes, coupled with the innovative application of the Taguchi-Gray Relational Analysis (TGRA) method for multi-objective optimization [16]. Moreover, an insightful exploration into the surface layer characteristics post-machining with various coatings including AlCrNi, Cr, and Ni, sheds light on the nuances of surface quality enhancement achievable through optimized conditions, as evidenced by meticulous analysis [17]. Furthermore, the simultaneous determination of Material Removal Rate (MRR) and Surface Roughness (SR) in EDM via coated electrodes underscores the novel approach of employing TGRA for holistic optimization [18].

A noteworthy contribution to the field is the significant improvement in optimal results achieved through the fusion of Taguchi methodology with Grey Relational Analysis (Taguchi-GRA), demonstrating promising prospects for enhanced EDM outcomes [19]. The amalgamation of Response Surface Methodology (RSM) with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for multi-objective decision-making in EDM represents a novel application yielding commendable results [20]. It's worth noting that the application of TGRA has been extended to numerous studies encompassing both EDM and micro-EDM with coated electrodes, consistently yielding insightful analyses and optimal results [21-25]. This collective effort not only underscores the versatility and effectiveness of multi-objective optimization methodologies in EDM but also highlights their potential for addressing complex machining challenges.

Addressing the imperative need for efficiency enhancement in machining processes, particularly for challenging materials like Ti-6Al-4V, this study embarks on the optimization journey of technological parameters in EDM employing coated electrodes. By meticulously analyzing and comparing quality indicators under optimal conditions, this research paves the way for informed decision-making towards achieving the most favorable outcomes. Additionally, the meticulous analysis and preliminary evaluation of machined surface quality under optimal conditions signify a significant step forward in advancing the understanding and practice of EDM methodologies.

In conclusion, the amalgamation of advanced optimization techniques with meticulous experimental analysis not only enriches the current understanding of EDM processes but also underscores the potential for groundbreaking advancements in machining efficiency and surface quality enhancement.

2. MATERIALS AND DESIGN METHOLOGY

The experimental investigation employed a Computer Numerical Control-Electrical Discharge Machining (CNC-EDM) machine, utilizing EDM oil (specifically, Dielectric Fluid 868 For Spark Erosion & EDM by Millers Oils) as the dielectric fluid.

Table 1. Process parameters and their levels for final experiments.

Process Parameters	**Levels**		
	1	2	3
Peak Current: I (A)	10	20	30
Gap Voltage: U (V)	40	45	50
Pulse-ON Time: T_{on} (μs)	100	500	1000

Quality indicators, specifically Material Removal Rate (MRR) and Tool Wear Rate (TWR), were employed to evaluate the experimental outcomes of the micro-EDM process. The technological parameters chosen for micro-EDM, including current (I), voltage (U), and pulse-on time (Ton), are presented in Table 1. The Taguchi method, recognized for its efficiency in EDM experimentation with a reduced number of trials, was utilized to meticulously design the experiment. This approach ensured a strategic and systematic exploration of the parameter space, resulting in the selection of the Taguchi design denoted as L16 for this investigation. The utilization of L16 facilitated 16 experimental runs, as delineated in Table 2, underscoring the innovative and methodical approach adopted in the optimization of micro-EDM processes.

However, the complexity inherent in determining multi-objective decisions via Taguchi necessitates the integration of complementary techniques. Therefore, in this research, Taguchi-TOPSIS was employed to simultaneously determine MRR and TWR in EDM using a graphene-coated electrode, with the procedural steps outlined in Figure 1.

The TOPSIS methodology offers practical models by allowing optimal indicators to be traded off, recognizing that improvements in one aspect may lead to trade-offs in others. Given the limited number of experiments conducted in the Taguchi method, it is imperative to determine the optimal results through S/N factor analysis, considering that the optimal values may not align with the parameters investigated directly. This underscores the importance of a comprehensive approach to optimizing micro-EDM processes, considering various factors to achieve robust and reliable results.

Table 2. Experimental results with graphene coated electrode.

Exp.	Input process parameters			Output Parameter	
	I (A)	U (V)	T_{on} (µs)	MRR (mg/min)	TWR (mg/min)
1	5	40	100	5.34	1.11
2	5	45	500	5.76	1.22
3	5	50	1000	6.25	1.48
4	5	55	1500	6.57	1.59
5	10	40	500	6.49	1.59
6	10	45	100	6.2	1.59
7	10	50	1500	7.12	2.21
8	10	55	1000	7.12	1.96
9	20	40	1000	7.75	2.84
10	20	45	1500	8.27	3.21
11	20	50	100	7.59	2.69
12	20	55	500	8.35	3.32
13	15	40	1500	7.51	2.32
14	15	45	1000	7.43	2.32
15	15	50	500	7.3	2.32
16	15	55	100	7.07	2.29

3. RESULTS AND DISCUSSION

3.1 Integration of Taguchi and Topsis methods

The amalgamation of the Taguchi and Topsis methods, outlined in Figure 1, provides a systematic and balanced approach to multi-objective optimization, presenting a novel dimension to our research methodology.

3.2 Optimal experiment determination via Topsis's Method

Step 1: Criterias matrix:

The initial step involved the creation of a criteria matrix, emphasizing the pivotal factors influencing the multi-objective optimization process.

$$X=\begin{bmatrix} MRR_1 & TWR_1 \\ MRR_2 & TWR_2 \\ & \\ & \\ MRR_{16} & TWR_{16} \end{bmatrix}$$

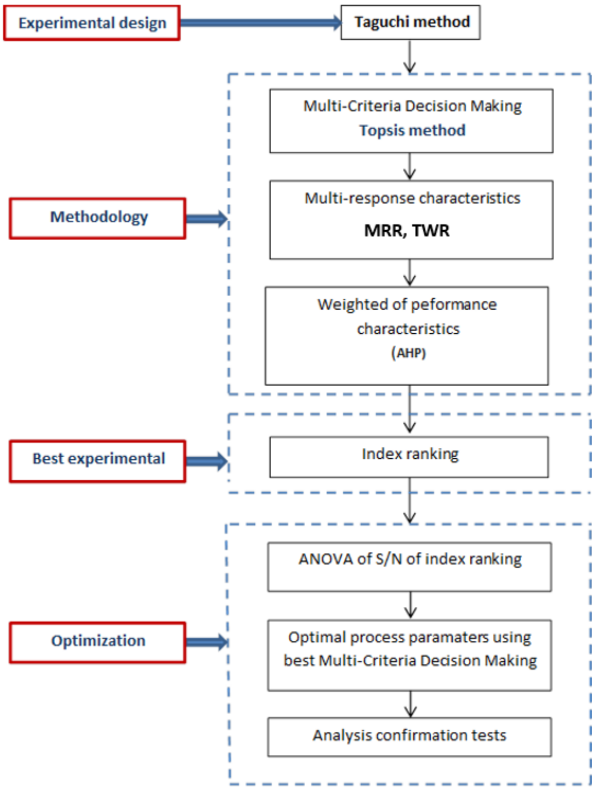


Fig. 1. Steps by Taguchi – Topsis.

Step 2: Normalize the Criterias matrix:

Normalization of the criteria matrix was performed, and the resulting normalized data is presented in Table 3. This step ensures fair comparisons and unbiased evaluations.

Step 3: Weight of quality indicators:

Utilizing the Analytic Hierarchy Process (AHP), the weights for Material Removal Rate (MRR) and Tool Wear Rate (TWR) were determined as WMRR = 0.667 and WTWR = 0.333. Table 3 illustrates the weight assignments for each quality criterion.

Step 4: Best and Worst Solutions:

The identification of the best solution (A+) and the worst solution (A-) was achieved, yielding A+ = {MRR=0.197; TWR=0.042} and A- = {MRR=0.126; TWR=0.124}.

Table 3. Normalized data.

Exp. No	I (A)	U (V)	Ton (μs)	Vector normalization	
				XMRR	**XTWR**
1	5	40	100	0.1892	0.1247
2	5	45	500	0.2041	0.1371
3	5	50	1000	0.2215	0.1663
4	5	55	1500	0.2328	0.1786
5	10	40	500	0.2300	0.1786
6	10	45	100	0.2197	0.1786
7	10	50	1500	0.2523	0.2483
8	10	55	1000	0.2523	0.2202
9	20	40	1000	0.2746	0.3190
10	20	45	1500	0.2930	0.3606
11	20	50	100	0.2689	0.3022
12	20	55	500	0.2959	0.3730
13	15	40	1500	0.2661	0.2606
14	15	45	1000	0.2633	0.2606
15	15	50	500	0.2587	0.2606
6	15	55	100	0.2505	0.2573

Steps 5-7: Calculations, C, and Ranking*

In-depth calculations, determination of C* values, and subsequent ranking outcomes are presented in Table 4. The best experiment, as indicated by the ranking, was the 4th experiment, resulting in optimal parameters: U = 55 V, I = 5 A, Ton = 1500 μs, MRR = 6.57 mg/min, and TWR = 1.59 mg/min.

3.3 Optimal results via S/N analysis

S/N values, determined by formula (1), identified optimal technological parameters through Topsis. Figure 2 showcases the optimal parameters aligning with experiment number 8, yielding MRR = 7.12 mg/min and TWR = 1.96 mg/min.

The S/N value is determined by formula (1). Figure 2 has shown that the optimal technological parameters performed by Topsis such as U = 55 V, I = 10 A and Ton = 1000 μs, and the optimal result coincides with experiment number 8th with MRR = 7.12 mg/min and TWR = 1.96 mg/min. The evaluation of quality indicators at optimal conditions, represented by the Signal-to-Noise (S/N) ratio as determined by equation (4), has been compared with the ranking results derived from the Composite Index (C*) in Table 4. It is evident from the analysis that the results obtained through S/N analysis exhibit lower significance compared to those derived from the C* rating. Consequently, the technological parameters and quality indices for the optimal study will be conclusively determined based on the ranking provided by C*. This underscores the robustness and reliability of the Composite Index in guiding the selection of optimal parameters in the context of our study. The higher significance attributed to the C* ranking reinforces its efficacy as a decisive factor in identifying the most favorable conditions in Electrical Discharge Machining (EDM) with coated electrodes.

$$(MRR, TWR)OPT = I2 + U4 + Ton3 - 3.\ T \tag{4}$$

Table 4. Calculation results in Topsis and S/N ratio values.

Exp. No	y'_{MRR}	y'_{TWR}	y^{+}_{MRR}	y^{+}_{TWR}	y^{-}_{MRR}	y^{-}_{TWR}	S_i^+	S_i^-	C_i^*	Ranking	S / N ratio
1	0.126	0.042	-0.071	0.000	0.000	-0.083	0.0711	0.0827	0.538	10	-5.38435
2	0.136	0.046	-0.061	0.004	0.010	-0.079	0.0613	0.0792	0.563	5	-4.98983
3	0.148	0.055	-0.050	0.014	0.022	-0.069	0.0515	0.0721	0.583	4	-4.68663
4	0.155	0.059	-0.042	0.018	0.029	-0.065	0.0457	0.0709	0.608	1	-4.32193
5	0.153	0.059	-0.044	0.018	0.027	-0.065	0.0475	0.0702	0.596	3	-4.49507
6	0.147	0.059	-0.051	0.018	0.020	-0.065	0.0539	0.0678	0.557	7	-5.08290
7	0.168	0.083	-0.029	0.041	0.042	-0.042	0.0504	0.0591	0.540	9	-5.35212
8	0.168	0.073	-0.029	0.032	0.042	-0.051	0.0431	0.0660	0.605	2	-4.36489
9	0.183	0.106	-0.014	0.065	0.057	-0.018	0.0663	0.0597	0.474	14	-6.48443
10	0.195	0.120	-0.002	0.079	0.069	-0.004	0.0786	0.0694	0.469	15	-6.57654
11	0.179	0.101	-0.018	0.059	0.053	-0.024	0.0618	0.0582	0.485	13	-6.28517
12	0.197	0.124	0.000	0.083	0.071	0.000	0.0827	0.0711	0.462	16	-6.70716
13	0.177	0.087	-0.020	0.045	0.051	-0.037	0.0494	0.0635	0.562	6	-5.00527
14	0.176	0.087	-0.022	0.045	0.049	-0.037	0.0502	0.0620	0.552	8	-5.16122
15	0.173	0.087	-0.025	0.045	0.046	-0.037	0.0516	0.0595	0.536	11	-5.41670
16	0.167	0.086	-0.030	0.044	0.041	-0.039	0.0535	0.0562	0.512	12	-5.81460

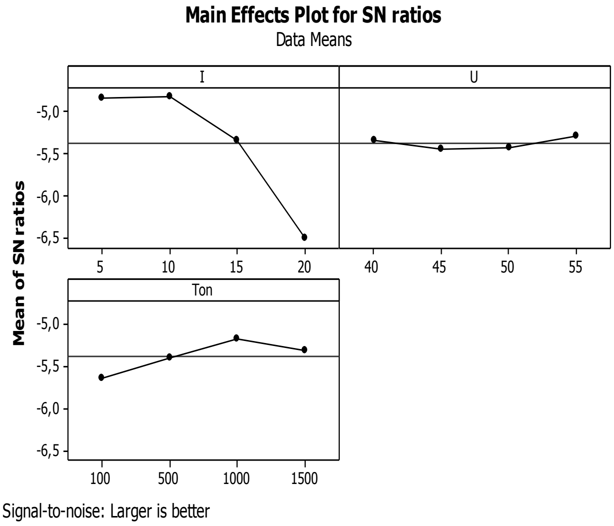


Fig. 2. Analysis of S/N of topsis.

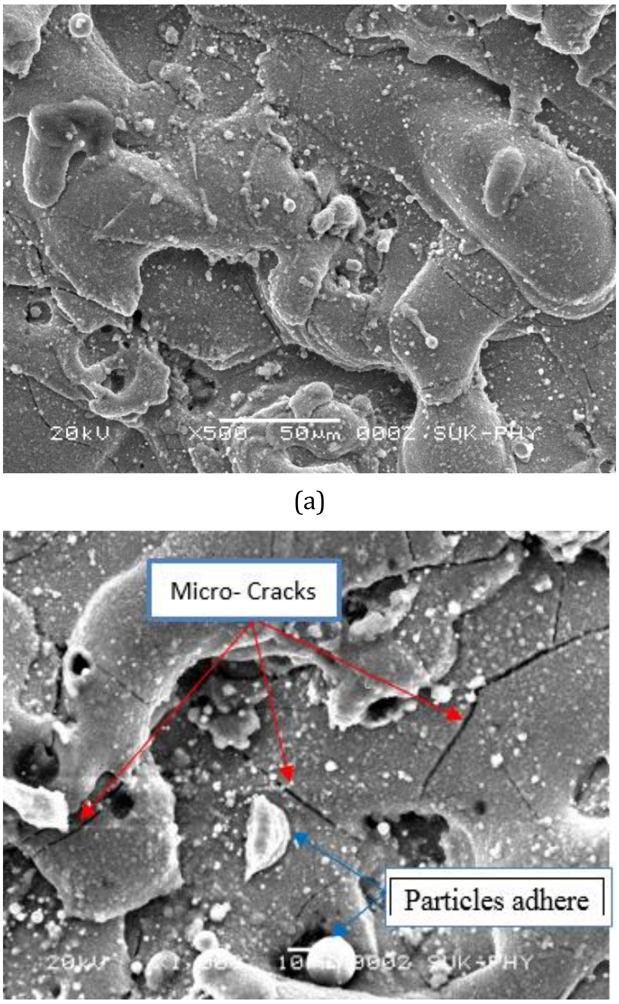
Table 5 also provides a comprehensive comparison between the results obtained through Topsis and S/N analysis. The significance of the results from C* ranking surpasses those derived from S/N analysis, underscoring the importance of the former in determining technological parameters and quality indices for optimal conditions.

Table 5. Comparison between topsis and S/N analysis.

Quality indicators	Ranking	S/N ratio	Improvement (%)
MRR (mg/min)	6.57	7.12	8.32
TWR (mg/min)	1.59	1.96	23.4

3.4. Surface Quality at Optimal Conditions

Detailed examination of the machined surface topography revealed numerous craters distributed irregularly (Figure 3a), attributed to the formation and random distribution of sparks in the discharge gap. Adhered particles and microcracks were observed on the machined surface (Figure 3b), resulting from the melting of electrode material and workpiece by sparks, rapidly cooled by the dielectric solution. A distinctive white layer on the machined surface (Figure 4), formed by the melting of electrode material and workpiece, adds an additional layer of complexity to the post-machining workability. These findings contribute valuable insights into the surface characteristics under optimal conditions, further enhancing the understanding of the outcomes of EDM with coated electrodes.



(a)

(b)

Fig. 3. Topography of machined surface after EDM.

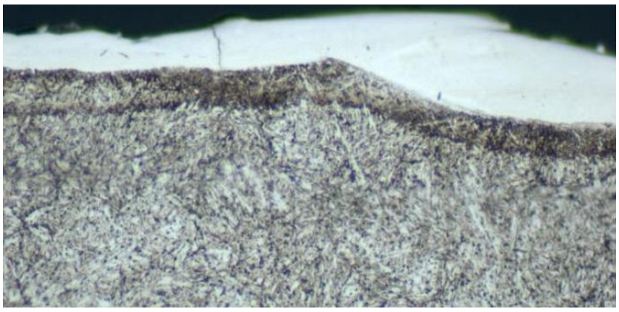


Fig. 4. White layer of machined surface after EDM.

4. CONCLUSIONS

The comprehensive investigation into multi-objective optimization within Electrical Discharge Machining (EDM), employing a graphene-coated aluminum (Al) electrode for Ti-6Al-4V, has culminated in several discerning conclusions, underlining the innovation and impact of this study:

- The employed calculation methodology, characterized by its simplicity and brevity, facilitates the seamless application of the Taguchi-Topsis approach in multi-objective decision-making. The consistency exhibited in the results underscores the reliability and accessibility of this computational framework.
- The assessment of the Composite Index (C*) attests to its robust nature, substantiating its effectiveness in determining optimal outcomes. The consistently favorable results obtained through C* ranking affirm its reliability as a key metric for discerning optimal process parameters in the intricate EDM landscape with coated electrodes.
- The study successfully identifies and substantiates the optimal process parameters essential for EDM utilizing a graphene-coated electrode. Specifically, the configuration of U = 55 V, I = 5 A, and Ton = 1500 µs emerges as the optimal combination, resulting in a Material Removal Rate (MRR) of 6.57 mg/min and a Tool Wear Rate (TWR) of 1.59 mg/min.
- Post-EDM machining analysis at optimal conditions reveals a significant transformation in surface quality. The observed changes necessitate further in-depth studies to evaluate the impact on the functionality and operational efficacy of the end product. This notable alteration in surface quality emphasizes the potential influence of the proposed optimal process parameters on the overall characteristics of the machined product.

REFERENCES

[1] A. Uğur, E. Nas, and H. Gökkaya, "Investigation of the machinability of SiC reinforced MMC materials produced by molten metal stirring and conventional casting technique in die-sinking electrical discharge machine," *Int. J. Mech. Sci.,* vol. 186, p. 105875, Nov. 2020, doi: 10.1016/j.ijmecsci.2020.105875.

[2] E. Nas and F. Kara, "Optimization of EDM machinability of hastelloy C22 super alloys," *Machines*, vol. 10, no. 12, p. 1131, Nov. 2022, doi: 10.3390/machines10121131.

[3] T. Ablyaz, K. Muratov, S. B. Preetkanwal, and S. S. Sarabjeet, "Experimental investigation of wear resistance of copper coated electrode-tool during electrical discharge machining," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 510, p. 012001, Apr. 2019, doi: 10.1088/1757-899x/510/1/012001.

[4] P. Mandal and S. C. Mondal, "Performance analysis of copper-based MWCNT composite coated 316L SS tool in electro discharge machining," *Machining Sci. Technol.*, vol. 25, no. 3, pp. 422–437, Jan. 2021, doi: 10.1080/10910344.2020.1855652.

[5] K. Karunakaran and M. Chandrasekaran, "Investigation of machine-ability of inconel 800 in EDM with coated electrode," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 183, p. 012014, Mar. 2017, doi: 10.1088/1757-899x/183/1/012014.

[6] A.-H. Chiou, C.-C. Tsao, and C.-Y. Hsu, "A study of the machining characteristics of micro EDM milling and its improvement by electrode coating," *Int. J. Adv. Manuf. Technol.*, vol. 78, no. 9-12, pp. 1857–1864, Jan. 2015, doi: 10.1007/s00170-014-6778-3.

[7] S. S. Shirguppikar and M. S. Patil, "Experimental investigation on micro-electro discharge machining process using tungsten carbide and titanium nitride-coated micro-tool electrode for machining of Ti-6Al-4V," *Advances Mater. Process. Technol.*, pp. 1–18, Oct. 2020, doi: 10.1080/2374068x.2020.1833399.

[8] H. Huang, A. B. Yang, and C. Y. Hsu, "The optimization of micro EDM milling of Ti–6Al–4V using a grey Taguchi method and its improvement by electrode coating," *Int. J. Adv. Manuf. Technol.*, vol. 96, no. 9-12, pp. 3851–3859, Mar. 2018, doi: 10.1007/s00170-018-1841-0.

[9] S. Mishra, "Analyzing the machining effectiveness of EDM on inconel 718 using copper and graphite electrode," *YMER Digit.*, vol. 21, no. 08, pp. 343–352, Aug. 2022, doi: 10.37896/ymer21.08/30.

[10] L. Panchal, S. K. Biradar, and V. Y. Gosavi, "Analysis of EDM process parameters by using coated electrodes," *Int. J. Eng. Trends Technol.*, vol. 41, no. 4, pp. 181–185, Nov. 2016, doi: 10.14445/22315381/ijett-v41p234.

[11] P. Mandal and S. C. Mondal, "Performance analysis of copper-based MWCNT composite coated 316L SS tool in electro discharge machining," *Machining Sci. Technol.*, vol. 25, no. 3, pp. 422–437, Jan. 2021, doi: 10.1080/10910344.2020.1855652.

[12] S. K. Baral, P. Pallavi, and A. Utkarshaa, "Effect of nichroloy coated electrode on machining performance of electrical discharge machining using Inconel 625," *Mater. Today: Proc.*, vol. 45, pp. 7894–7900, Jan. 2021. doi: 10.1016/j.matpr.2020.12.615.

[13] J.Prasanna, S. Rajamanickam, O. A. Kumar, G. Karthick Raj, and P. V. V. S. Narayanan, “MRR and TWR evaluation on electrical discharge machining of Ti-6Al-4V using tungsten : Copper composite electrode,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 197, p. 012087, May 2017, doi: 10.1088/1757-899x/197/1/012087.

[14] Uhlmann, S. Rosiwal, K. Bayerlein, and M. Röhner, “Influence of grain size on the wear behavior of CVD diamond coatings in micro-EDM,” *Int. J. Adv. Manuf. Technol.*, vol. 47, no. 9-12, pp. 919–922, Jun. 2009, doi: 10.1007/s00170-009-2131-7.

[15] W. Yuangang, Z. Fuling, and W. Jin, “Wear-resist Electrodes for Micro-EDM,” *Chin. J. Aeronaut.*, vol. 22, no. 3, pp. 339–342, Jun. 2009, doi: 10.1016/s1000-9361(08)60108-9.

[16] N. H. Phan et al., “Multi-object optimization of EDM by Taguchi-DEAR method using AlCrNi coated electrode,” *Int. J. Adv. Manuf. Technol.*, vol. 116, no. 5-6, pp. 1429–1435, Apr. 2021, doi: 10.1007/s00170-021-07032-3.

[17] H.-Y. Hsu and C.-C. Hu, “Surface quality improvement of EDMed Ti–6Al–4V alloy using plasma etching and TiN coating,” *Int. J. Adv. Manuf. Technol.*, vol. 88, no. 1-4, pp. 67–74, Apr. 2016, doi: 10.1007/s00170-016-8760-8.

[18] S. K. Baral, P. Pallavi, and A. Utkarshaa, “Effect of nichroloy coated electrode on machining performance of electrical discharge machining using Inconel 625,” *Mater. Today: Proc.*, vol. 45, pp. 7894–7900, Jan. 2021. doi: 10.1016/j.matpr.2020.12.615.

[19] K. Ponappa, K. S. K. Sasikumar, M. Sambathkumar, and M. Udhayakumar, “Multi-objective optimization of EDM process parameters for machining of hybrid aluminum metal matrix composites (al7075/tic/b4c) using genetic algorithm,” *Surf. Rev. Lett.*, vol. 26, no. 10, p. 1950071, Nov. 2019, doi: 10.1142/s0218625x19500719.

[20] M. Kolli, A. V. S. Ram Prasad, and D. S. Naresh, “Multi-objective optimization of AAJM process parameters for cutting of B4C/Gr particles reinforced Al 7075 composites using RSM-TOPSIS approach,” *SN Appl. Sci.*, vol. 3, no. 7, Jun. 2021, doi: 10.1007/s42452-021-04699-x.

[21] N. H. Phan et al., “Multi-object optimization of EDM by Taguchi-DEAR method using AlCrNi coated electrode,” *Int. J. Adv. Manuf. Technol.*, vol. 116, no. 5-6, pp. 1429–1435, Apr. 2021, doi: 10.1007/s00170-021-07032-3.

[22] P. N. Huu et al., “Multi-objects optimization in μ-EDM using AlCrNi-coated tungsten carbide electrode for Ti-6AL-4 V,” *Int. J. Adv. Manuf. Technol.*, Sep. 2022, doi: 10.1007/s00170-022-10022-8.

[23] P. H. Nguyen et al., “Application of tgra-based optimisation for machinability of high-chromium tool steel in the EDM process,” *Arabian J. Sci. Eng.*, vol. 45, no. 7, pp. 5555–5562, Mar. 2020, doi: 10.1007/s13369-020-04456-z.

[24] N. H. Phan et al., “Tool wear rate analysis of uncoated and alcrni coated aluminum electrode in EDM for ti-6al-4 V titanium alloy,” *Advances in Engineering Research and Application. Cham: Springer Int. Publishing*, pp. 832–838, 2020, doi: 10.1007/978-3-030-64719-3_91.

[25] N. H. Phan et al., “Material removal rate in electric discharge machining with aluminum tool electrode for ti-6al-4v titanium alloy,” *Advances in Engineering Research and Application. Cham: Springer Int. Publishing*, pp. 527–533, 2020, doi: 10.1007/978-3-030-64719-3_58.