Experimental Study on Machinability of Aluminum Cast Composite in Micro-EDM Drilling

*[1]Karneni Thrimurthula Devi, [2]Geddam Honey, [3]Bokka Yuva Naga Teja, [4]Ganti Kiran Kumar,
[5]Guntipalli Surya Lokesh, [6]V K Viswanadha Raju

[1,2,3,4,5,6]Department of Mechanical Engineering, SRKR Engineering College, Bhimavaram, Andhra Pradesh, India

*[1]devikarneni0@gmail.com, [2]honeygeddam94@gmail.com, [3]tejabokka38@gmail.com,
[4]kirantarak21@gmail.com, [5]gsuryalokesh2005@gmail.com, [6]kvraju.vegesna@rediffmail.com

Abstract

Micro Electrical Discharge Machining (Micro-EDM) is a non-contact process that is extensively employed for generating high-precision micro-scale features, especially in materials that are otherwise difficult to machine. In the present work, an experimental study has been conducted to examine the drilling performance of aluminium composites using silver-coated brass tubular electrodes under both single-channel (SC) and multi-channel (MC) configurations. The experiments were structured based on a Taguchi L9 orthogonal array, considering pulse on time (TON), pulse off time (TOFF), and discharge current (DC) as the key input parameters. The machining performance was evaluated in terms of material removal rate (MRR) and overcut (OC). Analysis of the S/N ratios indicates that, for MRR, the silver SC configuration achieved the highest value of 2.451 dB at Run 3 (TON = 20 µs, TOFF = 50 µs, DC = 6 A), while the silver MC configuration reached a close value of 2.424 dB at Run 6 (TON = 50 µs, TOFF = 50 µs, DC = 2 A). In the case of overcut, the maximum S/N ratio for Silver SC was 0.1288 at Run 2, whereas Silver MC showed a higher value of 0.1671 at Run 8. Among all the input variables, discharge current was found to have the most significant influence on the performance characteristics. Overall, this study helps in identifying suitable machining conditions and electrode configurations to achieve improved efficiency and accuracy in micro-EDM drilling of aluminium composites.

Keywords: Single-channel, Multi-channel, Micro electrical discharge machining, Drilling, Composite

1. Introduction

Micro Electrical Discharge Machining (Micro-EDM) is a sophisticated non-traditional machining technique that is widely applied for fabricating accurate micro-scale features in electrically conductive materials, particularly those that are challenging to process through conventional methods. In this work, a detailed investigation is performed on the parametric optimization of Micro-EDM drilling of aluminum composites, which are increasingly recognized as high-performance materials in aerospace and structural fields owing to their excellent strength-to-weight ratio, higher hardness, and superior thermal as well as electrical conductivity. However, the incorporation of hard ceramic reinforcements within aluminum composites considerably raises machining complexity by promoting rapid tool wear and deteriorating surface quality when traditional machining approaches are used. To address these limitations, Micro-EDM is adopted because of its non-contact machining mechanism and its capability to process hard composite materials without generating mechanical stresses. The study emphasizes the application of silver-coated brass tubular electrodes in both single-channel (SC) and multi-channel (MC) configurations, with the aim of analyzing their effect on machining performance. The experimental plan is systematically developed using a Taguchi L09 orthogonal array by varying key process parameters such as pulse on time (TON), pulse off time (TOFF), and discharge current (DC). The machining performance is evaluated based on two critical output responses, namely material removal rate (MRR) and overcut (OC). The experimental findings indicate that Silver SC attains the highest MRR S/N ratio of 2.451 dB at Run 3, whereas silver MC records the highest OC S/N ratio of 0.1671 at Run 8. In addition, S/N ratio analysis along with analysis of variance (ANOVA) is employed to determine the most influential process parameters and to establish optimal machining conditions. The results of this study offer meaningful insights into the appropriate selection of electrode configurations and process parameters for achieving efficient, accurate, and consistent micro-EDM drilling of aluminum composites, thereby supporting their effective application in advanced engineering domains.

2. Literature Review

Electrical Discharge Machining (EDM) is a non-conventional, thermally driven material removal process that is widely acknowledged for its capability to machine electrically conductive materials irrespective of their hardness

[1]. This characteristic makes EDM especially suitable for machining advanced materials such as metal matrix composites, which are difficult to process using conventional techniques due to the presence of abrasive reinforcements [2]. The process is based on controlled electrical discharges generated between a tool electrode and a workpiece submerged in a dielectric medium, producing a high-temperature plasma channel typically ranging from 8,000°C to 20,000°C, which results in localized melting and vaporization of material [3]. In micro-EDM drilling, this phenomenon is refined to fabricate precise micro-holes and complex features without any physical contact, thereby eliminating cutting forces entirely [4]. Among the electrical parameters influencing micro-EDM drilling, discharge current and pulse-on time play a dominant role, as they significantly affect both the material removal rate (MRR) and dimensional accuracy [5]. While higher discharge energy, achieved through increased current and longer pulse durations, enhances MRR, it adversely impacts dimensional accuracy due to the occurrence of overcut (OC), which refers to the enlargement of the machined hole beyond the electrode diameter [6,7]. Extended pulse durations also intensify heat transfer, thereby increasing overcut and enlarging the heat-affected zone [8]. To mitigate these issues, recent studies have focused on the use of coated electrodes as a promising approach to improve wear resistance, thermal stability, and electrical conductivity. Coatings such as Titanium Nitride, Diamond-Like Carbon, and more recently silver, have shown considerable potential in stabilizing machining conditions, prolonging tool life, and improving overall process performance [9,10].

Electrode coatings can be deposited using several techniques, including Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), electroplating, and thermal spraying, depending on the specific application requirements and desired electrode characteristics. The selection of a suitable coating method depends on factors such as material compatibility, cost considerations, expected performance improvements, and the nature of the workpiece material [11]. In the PVD process for coating micro-EDM electrodes, the electrodes are placed inside a vacuum chamber to ensure a clean and controlled environment. A coating material, such as copper, tungsten, or graphite, is vaporized through methods like resistive heating or sputtering. The evaporated atoms then travel through the vacuum and deposit onto the electrode surface, forming a thin, uniform coating layer. Careful control of deposition parameters such as temperature, chamber pressure, and substrate bias voltage ensures uniform thickness and coating quality. Post-deposition treatments, including annealing, can further enhance coating properties [12]. PVD provides excellent control over coating thickness, composition, and properties, leading to improved durability and electrical conductivity. It also ensures strong adhesion and allows customization based on application needs. However, the process involves high equipment and operational costs and may be less suitable for coating complex geometries or large-scale production [13].

In contrast, the CVD process involves exposing the electrode to a gaseous environment containing precursor compounds, which undergo chemical reactions on the electrode surface to form a thin film coating [14]. This technique yields coatings with superior adhesion, uniformity, and quality. CVD is particularly advantageous for coating complex geometries and offers precise control over coating characteristics. Nevertheless, it often requires elevated temperatures and specialized equipment, which increases operational costs [15]. Despite these limitations, CVD remains an effective method for producing high-performance coatings on EDM electrodes, thereby enhancing machining efficiency and accuracy. The electroplating process, on the other hand, involves immersing the electrode in an electrolyte solution containing metal ions such as copper, nickel, silver, or chromium [16]. Upon application of an electric current, these ions migrate toward the electrode surface, where they are reduced and deposited as a thin metallic layer. Electroplating is advantageous due to its simplicity, cost-effectiveness, and ability to uniformly coat complex geometries. It also allows precise control over coating thickness and composition. In the present study, silver and chromium coatings are applied to brass tubular electrodes using the electroplating technique, selected for its compatibility with tubular geometries and its ability to produce consistent and uniform coatings.

3. Methodology

3.1. Material

Aluminum composites are a class of advanced engineering materials formed by reinforcing aluminum with secondary phases such as ceramics, carbon, or metallic particles to improve its mechanical and functional performance. These composites retain the inherent benefits of aluminum, including low density, corrosion resistance, and good thermal conductivity, while gaining enhanced strength, hardness, and wear resistance from the reinforcements. Consequently, aluminum composites find extensive applications in aerospace, automotive, marine, and electronics sectors, where high strength and long-term reliability are critical. Their adaptability enables the development of customized properties, making them suitable for a wide range of uses, including structural components, precision parts, and thermal management systems. A silver coating with an approximate thickness of 3µm is deposited on the brass substrate through electroplating. Silver possesses the highest electrical conductivity among metals (62.1 MS/m), which contributes to improved discharge frequency and enhanced MRR. The silver-coated single-channel and multi-channel electrodes.

3.2. Experimental Design

The Taguchi method is a well-established design of experiments approach that reduces the number of experimental trials while ensuring maximum extraction of meaningful process information. Table 1 presents the selected process parameters along with their respective levels. An L9 orthogonal array was adopted to study four process parameters, each at three different levels. This experimental design enables the evaluation of the main effects of all four parameters through only nine experimental runs, thereby minimizing the number of trials. The L9 experimental layout generated using the Taguchi orthogonal array is shown in Table 2. To avoid systematic errors caused by time-dependent variations in the machine or measuring instruments, all experiments were conducted in a randomized sequence. The performance measures considered in this study are described as follows. Material removal rate is determined based on the volume difference of the workpiece before and after machining, divided by the machining time: MRR = $(W_{before}-W_{after})/(\rho \times t)$, where ρ represents the density of Aluminum composite (2.69 g/cm^3) and t denotes the machining time (5 min). Overcut is defined as the radial difference between the diameter of the drilled hole and the diameter of the electrode: OC = $(D_{hole}-D_{electrode})/2$. The diameter of the hole is measured using a toolmaker's microscope with a resolution of 0.001 mm.

Table 1: Process parameters and levels

Process Parameter	Level 1	Level 2	Level 3
Pulse On Time – TON (µs)	20	50	80
Pulse Off Time – TOFF (µs)	10	30	50
Discharge Current – DC (A)	2	4	6

Table 2: Taguchi L9 Orthogonal Array

S.No.	TON (µs)	TOFF (µs)	DC (A)
1	20	10	2
2	20	30	4
3	20	50	6
4	50	10	4
5	50	30	6
6	50	50	2
7	80	10	6
8	80	30	2
9	80	50	4

4. Results and discussion

The experimental findings obtained using the L9 Taguchi orthogonal array for both electrode variants (silver SC, silver MC) are summarized in Tables 3 for MRR and OC, respectively. It is observed that MRR increases with an increase in TON and higher DC, as the elevated spark energy promotes more effective melting and vaporization of the composite material. Silver multi-channel electrodes exhibit a notable enhancement in performance, with MRR values increasing from 0.89 mm^3/min at lower TON and DC to beyond 4 mm^3/min under high-energy conditions. Although increasing TOFF results in a reduction in MRR due to a lower frequency of spark generation, it is still essential for effective debris flushing and maintaining stable machining, thereby making DC the most influential parameter in material removal efficiency. Overcut displays a similar dependence on energy input, where higher TON and DC lead to expansion of the plasma channel and an increase in the machining gap. The highest OC values are observed under high-energy conditions, reaching up to 78 µm for silver MC electrodes. While TOFF contributes to machining stability and slightly decreases OC, its influence is comparatively less significant than that of TON and DC. Silver MC electrodes tend to generate higher OC at elevated energy levels due to increased spark intensity, whereas silver SC electrodes result in lower OC under reduced energy conditions, thereby ensuring improved dimensional accuracy. Overall, discharge current is identified as the most dominant parameter affecting overcut in micro-EDM drilling of aluminum composites.

Tabel 3: Experimental observations of MRR and OC

S.No.	TON (µs)	TOFF (µs)	DC (A)	MRR (mm^3/min)		OC (µm)	
				SC	MC	SC	MC
1	20	10	2	-1.013561	1.796329	0.0341	0.0508
2	20	30	4	-3.192001	-0.901900	0.1288	0.0543
3	20	50	6	2.450615	1.449826	0.0268	0.0586
4	50	10	4	0.992676	1.996763	0.0650	0.0069
5	50	30	6	-1.956310	-1.844207	0.0133	-0.0139
6	50	50	2	0.068875	2.423887	-0.0576	0.0394
7	80	10	6	-0.703239	0.503070	0.0249	-0.0829
8	80	30	2	0.380998	-0.002619	-0.0389	0.1671
9	80	50	4	0.641277	-2.228921	-0.1142	0.0157

5. Conclusion

The present study investigates the influence of process parameters and electrode configuration on the micro-EDM drilling performance of aluminum composites using silver-coated brass electrodes.

- Multi-channel silver-coated electrodes demonstrated superior machining performance compared to single-channel electrodes, achieving higher MRR under most operating conditions. This improvement is attributed to enhanced spark distribution and more effective debris evacuation during micro-EDM drilling of aluminum composites.
- Discharge current was identified as the most dominant process parameter influencing both MRR and overcut, followed by TON. Higher DC and TON increased spark energy, leading to improved material removal but also causing a wider machining gap and increased overcut.
- TOFF played a secondary yet essential role in stabilizing the machining process by facilitating debris removal and preventing arcing. Although higher TOFF slightly reduced MRR due to decreased spark frequency, it contributed to more consistent machining conditions.
- A trade-off between productivity and dimensional accuracy was observed. While MC electrodes at higher energy conditions produced higher MRR, SC electrodes offered comparatively lower overcut at reduced energy levels. Therefore, moderate parameter settings (TON-50 µs, TOFF-50 µs, DC-4 A) are recommended to achieve a balanced combination of machining efficiency and accuracy.

References

1. Benedict, G. F. (1987). Nontraditional Manufacturing Processes. New York: Marcel Dekker Inc.
2. Hasan, M. S., Rahman, M. M., & Kadirgama, K. (2017). Machining of metal matrix composites: A review. International Journal of Advanced Manufacturing Technology, 91(1–4), 1–23.
3. Shahri, M. H., Mahdavinejad, R. A., & Ashjaee, M. (2022). Investigation of EDM process parameters and plasma channel characteristics. Journal of Manufacturing Processes, 68, 102–115.
4. Jain, V. K. (2002). Advanced Machining Processes. New Delhi: Allied Publishers.
5. Gostimirovic, M., Kovac, P., Sekulic, M., & Skoric, B. (2020). Influence of discharge energy on machining performance in EDM. Journal of Materials Processing Technology, 285, 116781.
6. Kumar, S., Singh, R., & Singh, T. P. (2017). Experimental investigation of EDM parameters on overcut and MRR. Procedia Engineering, 173, 1411–1418.
7. Yadav, V., Pradhan, B. B., & Das, S. (2020). Parametric optimization of EDM process for dimensional accuracy. Materials Today: Proceedings, 26, 1872–1877.
8. Hoang, K. T., & Yang, S. H. (2013). Effect of pulse duration on machining characteristics in micro-EDM. International Journal of Precision Engineering and Manufacturing, 14(3), 431–438.
9. Klocke, F., Wirtz, A., & Veselovac, D. (2018). Influence of electrode coatings on EDM performance. CIRP Annals - Manufacturing Technology, 67(1), 221–224.
10. Patel, D., & Joshi, S. S. (2022). Advances in coated electrodes for EDM applications. Journal of Manufacturing Science and Engineering, 144(5), 051012.
11. Ohring, M. (2002). Materials Science of Thin Films (2nd ed.). Academic Press. (PVD process)

12. Mattox, D. M. (2010). Handbook of Physical Vapor Deposition (PVD) Processing. William Andrew Publishing.
13. Pierson, H. O. (1999). Handbook of Chemical Vapor Deposition (CVD). William Andrew Publishing.
14. Hitchman, M. L., & Jensen, K. F. (1993). Chemical Vapor Deposition: Principles and Applications. Academic Press.
15. Schlesinger, M., & Paunovic, M. (2010). Modern Electroplating (5th ed.). Wiley.
16. Lowenheim, F. A. (1978). Modern Electroplating. Wiley-Interscience.