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Original Article

Investigating FDM Electrodes for EDM Machining of Mild Steel: Performance Evaluation

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Abstract - *The purpose of this study is to analyze the performance of the tool electrode used in mild steel Electrical Discharge Machining (EDM) that is produced using the Fused Deposition Modeling (FDM) technique. The study evaluates the suitability of FDM-generated electrodes compared to traditional manufacturing methods and explores the effect of various process parameters on machining performance. Data from the experiments were analyzed using statistical techniques, including ANOVA, to determine significant correlations between process variables and key performance metrics such as Surface Roughness (SR) and Material Removal Rate (MRR). The results indicate that FDM-produced electrodes exhibit comparable performance to traditionally manufactured electrodes, with significant correlations observed between pulse-on-time, current, and voltage parameters and machining efficiency. The study highlights the potential of FDM technology as a cost-effective and efficient method for EDM electrode fabrication while also identifying areas for further research to optimize process parameters and explore advanced materials for enhanced performance.*

Keywords - *FDM, EDM, Tool electrode, Performance analysis, Additive manufacturing.*

1. Introduction

In modern manufacturing, the demand for precision, efficiency, and versatility has driven the exploration of innovative techniques for tool and part fabrication. Among these, EDM stands out as a pivotal process for shaping and machining electrically conductive materials with high accuracy. EDM removes material by creating a sequence of electrical discharges between a workpiece submerged in a dielectric fluid and the tool electrode. The electrode, which performs a critical role in this process, must possess specific characteristics to ensure optimal performance. Traditionally, tool electrodes for EDM have been manufactured using conventional methods such as milling, grinding, and wire EDM. While effective, these methods often entail prolonged lead times, high costs, and limited design flexibility. Moreover, the materials used in conventional electrode fabrication may not always meet the stringent requirements of EDM, particularly in terms of dimensional accuracy, surface finish, and electrode wear. This creates a significant research gap in optimizing electrode fabrication methods to meet these stringent requirements efficiently and cost-effectively. To address these challenges, additive manufacturing techniques have emerged as promising alternatives for EDM electrode fabrication. Among these, FDM has garnered significant attention due to its versatility, cost-effectiveness, and capacity to produce complex shapes with ease. FDM offers several advantages, including rapid prototyping capabilities, precise control over tool geometry, and the use of a wide range of materials tailored to specific EDM applications.

Previous research has explored various aspects of FDM technology and its application in EDM electrode fabrication. Ricky and Blom [1] conducted feasibility studies on producing EDM electrodes using rapid prototyping and electroforming processes, demonstrating the potential of additive manufacturing techniques in tooling applications. Arthur and Dickens [2] investigated the heat distribution in stereolithography electrodes during EDM, highlighting the importance of understanding thermal properties for efficient machining. Amorim et al. [3] explored rapid tooling of EDM electrodes using laser sintering, emphasizing the role of process parameters in achieving desired electrode quality. John Kechagias et al. [4] evaluated plating techniques for rapid EDM tooling, showcasing the importance of surface treatments in enhancing electrode performance. Oniszczuk et al. [5] analyzed the wear properties of EDM electrodes made by SLS, underscoring the influence of material composition and post-processing techniques on electrode durability. S. Arya et al. [6] investigated complex rapid EDM electrodes prepared by stereolithography and direct metal laser sintering, highlighting challenges in achieving uniform copper deposition for improved machining accuracy.

Ishfaq et al. [7] validated EDM electrodes made with rapid tooling technologies, emphasizing the importance of material selection and electrode design in achieving desired machining outcomes. Kechagias et al. [4] reviewed research on EDM electrode manufacture using rapid tooling, identifying gaps in process accuracy and electrode performance. Equbal et al. [8] examined the practicality of EDM electrode fabrication using FDM, highlighting the potential of additive manufacturing in tooling applications. Padhi et al. [9] studied electroless copper coating on ABS material for EDM tooling, demonstrating the effectiveness of surface treatment in enhancing electrode conductivity and performance. Reddy et al. [10] estimated the electrical conductivity of Acrylonitrile Butadiene Styrene and PLA-based EDM electrodes manufactured using FDM, providing insights into material selection for optimal machining outcomes. Sahu et al. [11] analyzed the performance of thick copper electroplated FDM ABS plastic electrodes in EDM, emphasizing the importance of electrode surface quality and dimensional accuracy. Equbal et al. [12] checked the feasibility of FDM in EDM electrode manufacturing, highlighting the challenges and opportunities associated with additive manufacturing processes. Danade et al. [13] tested the machining scenario of 3D-printed ABS electrodes copper coated in EDM, showcasing the potential of additive manufacturing technologies in improving electrode efficiency and cost-effectiveness. Awari et al. [14] conducted a pioneering study on real-time EDM utilizing FDM-produced electrodes. The authors analyzed the machining of EN-8 using copper electrodes versus FDM metalized electrodes. The metalized FDM electrodes, prepared by electroless plating copper onto FDM parts, exhibited comparable machining performance to solid copper electrodes. This study underscored the potential of FDM-generated electrodes as a viable alternative for EDM applications. In another study, researchers investigated the metallization of FDM-produced electrodes to enhance their electrical conductivity. By immersing FDM parts in different chemical compositions and durations, varying levels of conductivity were achieved. The results showed that electrodes with 100% fill material, immersed for an extended duration in a concentrated copper solution, exhibited the highest conductivity. This research highlighted the importance of surface preparation and chemical composition in optimizing electrode performance for EDM. Furthermore, recent advancements in FDM technology have led to the development of innovative materials tailored for EDM electrode fabrication. These materials offer improved thermal stability, electrical conductivity, and dimensional accuracy, addressing some of the limitations of traditional electrode materials [15]. For example, researchers have explored the use of carbon fiber-reinforced polymers and metal-infused filaments to enhance electrode durability and machining efficiency [16]. Additionally, studies have focused on optimizing process parameters and post-processing methods to further enhance the performance of FDM-generated electrodes. By fine-tuning parameters such as raster angle, layer thickness, and infill density, researchers have been able to achieve superior surface finish and dimensional accuracy in EDM machining. Post-processing treatments, such as heat treatment and surface coating, have also been investigated to improve electrode conductivity and wear resistance [17]. Moreover, the integration of FDM technology with other additive manufacturing processes, such as laser sintering and stereolithography, has shown promise in expanding the range of materials and geometries achievable for EDM electrode fabrication. These hybrid manufacturing approaches offer greater flexibility and customization options, allowing for the production of complex electrode designs with enhanced performance characteristics [18, 19].

The motive of this research article is to investigate the performance of tool electrodes fabricated through the FDM process during the EDM of mild steel. By analyzing key performance metrics such as SR and MRR, this study seeks to provide insights into the feasibility and effectiveness of FDM-generated electrodes in EDM applications.

2. Materials and Methods

2.1. Fabrication of EDM Tool Electrode by FDM Process

The EDM tool electrodes were manufactured using an FDM 3D printer. The FDM machine employed in this study was the model U Print SE Plus RP machine, equipped with a 0.4 mm diameter brass nozzle and a heated build platform. The thermoplastic material utilized for electrode fabrication was Acrylonitrile Butadiene Styrene (ABS). The material was chosen based on its compatibility with the FDM process and its mechanical properties suitable for EDM applications.

CAD models of the EDM tool electrodes were created using SolidWorks software. The electrode designs were based on the specific requirements of the EDM machining process, including electrode geometry, dimensions, and features. Once the CAD models were finalized, they were imported into the slicing software (Simplify3D) for toolpath generation. The FDM printing process was carried out according to the parameters shown in Table 1.

Table 1. Parameters for FDM manufacturing of EDM TOOL electrode

Parameter	Value
Infill Density	100%
Print Speed	60 mm/s
Layer Height	0.2 mm
Nozzle Temperature	220°C (for ABS) / 200°C (for PLA)
Build Plate Temperature	90°C (for ABS) / 60°C (for PLA)

The electrodes were printed layer by layer, with the thermoplastic filament extruded from the heated nozzle and placed onto the build platform. The printing process was monitored to ensure the dimensional accuracy and structural integrity of the electrodes.

After the FDM printing was completed, the electrodes underwent post-processing steps to enhance their electrical conductivity and surface finish. The printed electrodes were subjected to mechanical polishing using sandpaper and abrasive compounds to remove any surface imperfections and achieve a smooth finish. A conductive metal coating, copper, was applied to the surface of the electrodes using an electroless plating process. The electrodes were immersed in a chemical solution containing the metal ions, which were deposited onto the surface through a catalytic reaction. This metallization process improved the electrical conductivity of the electrodes, making them suitable for EDM applications.

2.2. Workpiece Material

The workpiece material selected for this study was mild steel, chosen due to its common use in various industrial applications and its compatibility with EDM processes. Mild steel offers adequate machinability and is often employed in manufacturing processes where precision and durability are paramount. Hence, the effectiveness of the electrodes is assessed in the EDM of mild steel, with dimensions measuring 120 × 60 × 5 mm³.

2.3. Method

The performance evaluation of the tool fabricated via the FDM process is conducted during the EDM of mild steel workpieces. A U Print SE Plus RP machine is used to perform the EDM, and commercial grade EDM 30 oil with a 0.763 (specific gravity) is used as the dielectric medium. The workpiece serves as the anode, and the tool electrode serves as the cathode in the machining arrangement.

Table 2. Process parameters with their levels

Symbol	Parameters	Units	Levels		
			-1	0	1
I	Current	Amp	5	10	15
Toff	Pulse off Time	microsecond	80	100	120
Ton	Pulse on Time	microsecond	50	75	100
V	Voltage	Volt	40	45	50

Four adjustable parameters are taken into account throughout the machining process: open circuit voltage (V), input current (I in amp), pulse on time (Ton in µs), and pulse off time (Toff in µs). In brief, these EDM parameters are explained as follows: The potential difference that is applied between the tool electrodes and the workpiece is known as the open circuit voltage (a). (b) Peak current: Also referred to as discharge current, this figure shows the greatest current that the power source or generator can provide for each pulse. (c) Length of pulse: This is also known as pulse-on-time or spark-on-time, and it indicates how long the current is permitted to travel between the electrode gap in a cycle. (d) Duty cycle: The ratio of pulse duration to the total cycle time.

In order to collect enough process-related data with fewer experimental runs, a DOE methodology, such as Taguchi's L25 experimental design, is utilized to conduct the experiments. Four parameters are taken into consideration in this experimental design, each at three levels, as Table 2 illustrates. Each experiment is conducted for 5 minutes. The performance measures considered include (1) MRR and (2) average SR of the machined surface. The performance measures obtained from Taguchi's L25 experimental design are tabulated in Table 3.

Table 3. Experimental performance and output performance measure

Run	Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2
	A: I	B: Ton	C: Toff	D: V	MRR	Ra
1	10	50	120	45	7.12901	5.86193
2	10	75	80	45	12.1761	6.16242
3	10	100	120	50	10.34	6.46951
4	15	100	80	50	52.5994	8.42569
5	15	75	120	50	31.8228	9.37416
6	15	100	80	40	50.4588	11.2103
7	10	50	80	50	10.9536	5.42929
8	10	75	100	40	9.17725	7.84687
9	15	50	100	45	27.7547	9.51862
10	5	75	100	50	7.97749	6.20426
11	15	50	80	40	31.5224	10.8324
12	15	75	120	40	29.3664	13.7137
13	10	75	100	40	9.34879	7.99354
14	10	75	100	40	9.69186	8.28688
15	10	100	120	40	9.10935	8.04206
16	5	100	80	40	6.19598	5.21299
17	5	50	100	45	8.71239	5.29556
18	5	50	120	50	16.3012	5.27848
19	5	50	80	40	3.22181	4.83053
20	10	75	80	45	12.0693	6.10836
21	10	75	120	45	7.18557	6.35287
22	5	75	100	50	7.68474	5.97658
23	5	75	120	40	6.83006	5.6394
24	15	100	100	45	42.3593	10.4871
25	15	100	100	45	43.1438	10.6813

2.3.1. MRR

The MRR is a measure of how quickly material is removed from the workpiece during machining. Equation (1) illustrates how MRR is derived from the workpiece's weight reduction during the EDM process.

$$MRR = \frac{(W_i - W_f)}{(t * \rho_w)} \tag{1}$$

Where,

Wi = Initial weight of the workpiece before machining

Wf = Final weight of the workpiece after machining

t = Total duration of EDM process

ρw = Density of the workpiece material, in this case, mild steel

2.3.2. Average Surface Roughness

With a Taylor-Hobson roughness tester, the machined surface's average SR is calculated. A sample span of 0.8 mm and a run-off length of 0.4 mm are used for measurement. The Ra value of each material is calculated three times, and the average is obtained for additional examination.

3. Result and Discussion

3.1. ANOVA

For the required response characteristics, process parameters with a p-value of less than 0.05 are deemed significant. The ANOVA approach is utilized for statistical evaluation of the outcomes. Surface roughness and MRR undergo different ANOVA analyses. The factorial design is appropriate for conducting tests, as confirmed by the Design-Expert software, which makes statistical interpretation of the experimental design data easier. The ANOVA feature of the Design-Expert software, which is described in reference [15], is used to compute statistical parameters such as adjusted R-squared (R2Adj), model F-value, Adequate Precision (AP), correlation coefficient (R2), lack of fit F-value, sum of squares (PRESS), predicted residual error, predicted R-squared (R2Pred) in order to determine the sufficiency and reliability of the models.

3.1.1. Statistical Interference of MRR

In this statistical analysis, the model obtained an F-value of 904.28, indicating its significance. The probability of such a high F-value occurring by chance alone is only 0.01%, suggesting that the model is reliable. Furthermore, the P-values < 0.05 confirm the significance of the model, while Lack of Fit, represented by an F-value of 7.9, is also deemed significant with a probability of only 0.203% occurring due to noise. Regarding the equation, the predicted R-squared value (0.9856) is close to the actual R-squared value (0.9992), with the difference between them being less than 0.2, indicating high model accuracy. Additionally, the precision value, calculated from the signal-to-noise ratio, is found to be 94.872, exceeding the preferable value of four, thus demonstrating a favorable signal-to-noise ratio.

3.1.2. Statistical Interference of Surface Roughness

In this statistical analysis, the model obtained an F-value of 125.94, indicating its significance. The probability of such a high F-value occurring by chance alone is only 0.01%, suggesting that the model is reliable. Furthermore, the P-values < 0.05 confirm the significance of the model, while the Lack of Fit, represented by an F-value of 4.17, is also deemed significant, with a probability of only 0.716% occurring due to noise. Regarding the equation, the predicted R-squared value (0.9128) is close to the actual R-squared value (0.9944), with the difference between them being less than 0.2, indicating high model accuracy.

Additionally, the precision value, calculated from the signal-to-noise ratio, is found to be 39.588, exceeding the preferable value of four, thus demonstrating a favorable signal-to-noise ratio.

3.2. Effect of Independent Parameter on MRR

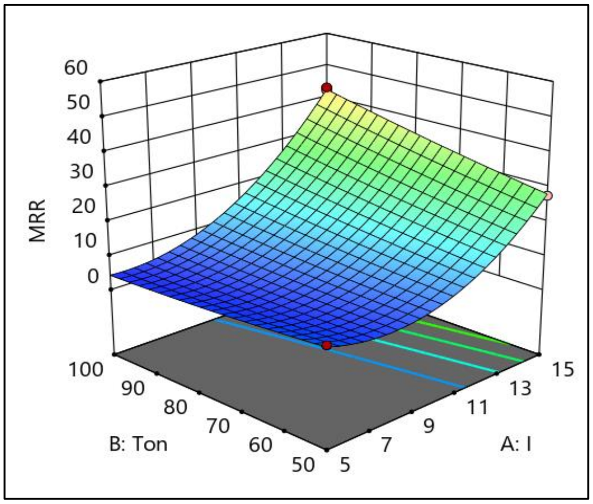
A regression equation for the material removal rate as a function of four input parameters has been developed using the experimental data from Table 3. Equation of regression for the real factor:

$$MRR = 56.35 - 4.75 \times I + 0.32 \times Ton + 0.46 \times Toff - 3.45 \times V + 0.0364 \times I \times Ton - 0.036 \times I \times Toff - 0.004 \times Ton \times Toff + 0.43 \times I^2 \tag{2}$$

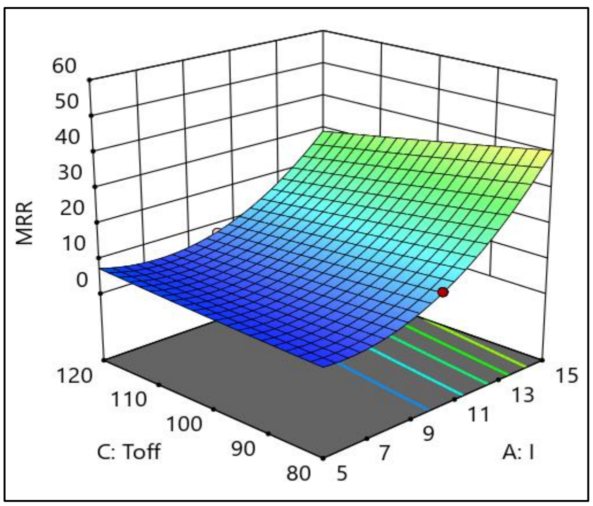
Figures 1(a), (b), and (c) display the response surface above, which was created to look at how process variables affect the rate of material removal. In the EDM process, the electron discharge rate is contingent upon the flow of current. Figure 1 illustrates that augmenting the current amplifies the MRR. This surge is attributed to an intensified electron discharge striking the work surface, leading to heightened material removal [20]. Likewise, an upsurge in voltage corresponds to an escalation in MRR. This can be ascribed to the voltage increase accelerating the current and current density [21].

Furthermore, extending the pulse-on-time intensifies the discharge of energy by prolonging the operation duration. The heightened energy discharge signifies material removal, thereby elevating the MRR [22]. From Figure 1(c), it is evident that the concurrent impact of current and voltage yields proportional outcomes. This aligns with the preceding discussion, which demonstrates that both voltage and current independently boost the MRR.

Consequently, their combined effect fosters a more robust and concentrated discharge between the electrodes, leading to increased material removal from the workpiece surface. Given the rising trends of both current and pulse-on-time in relation to MRR individually, their combined effect yields a rising curve with amplified interaction parameters, as depicted in Figure 1(a).



(a)



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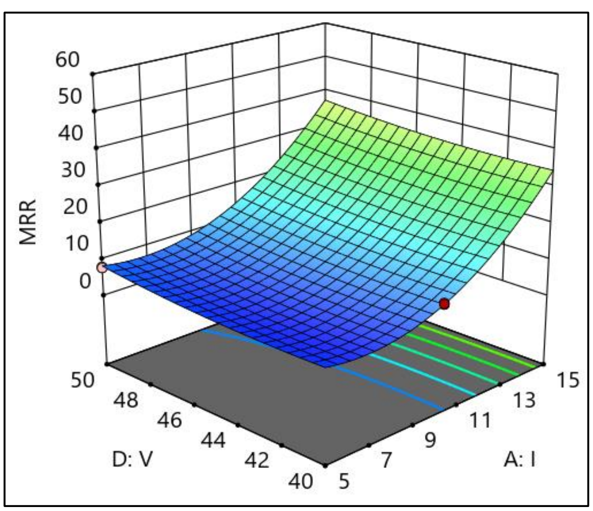


(c)

Fig. 1(a) Combined effect of Ton and I, (b) Combined effect of Toff and I, and (c) Combined effect of V and I on material removal rate.

3.3. Effect of Independent Parameter on Surface Roughness (Ra)

A regression equation for MR as a function of four input factors has been created using experimental data from Table 3. Equation of regression for the real factor:

$$Ra = 25.34 + 0.74 \times I + 0.03 \times Ton + 0.23 \times Toff - 1.57 \times V + 0.004 \times I \times Toff - 0.04 \times I \times V - 0.002 \times Toff \times V + 0.051 \times I^2 - 0.0007 \times Toff^2 + 0.022 \times V^2 \tag{3}$$

The response surface depicted in Figures 2(a), (b), and (c) above was created to look at how process variables affect the rate of material removal. As seen in Figure 2, an increase in current has been observed to raise Surface Roughness (SR). This is explained by the higher current, which amplifies the spark and leaves the workpiece surface with bigger craters [20]. The increased SR value is a result of these bigger craters [23].

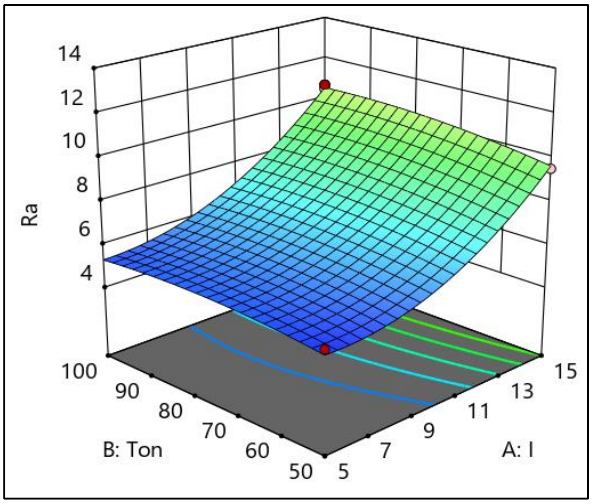
Discharge energy is the primary determinant of the machined surface quality. Because bigger craters emerge on the machined surface when discharge energy increases, MRR increases as well. On the machined surface, however, these huge craters lead to an uneven surface quality.

Peak current, open circuit voltage, and pulse-on-time all rise with increased spark energy, which in turn raises MRR. As a result, the size of the craters grows and the machined surface's average surface.

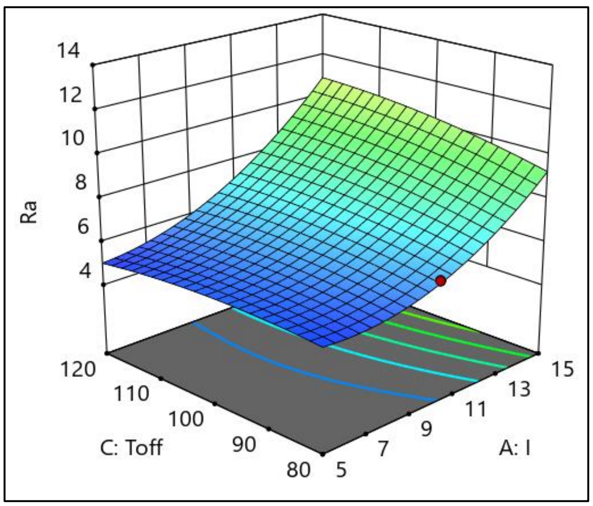
This research presents a significant advancement in EDM electrode fabrication by leveraging FDM technology, addressing the limitations of traditional methods such as milling, grinding, and wire EDM. While these conventional methods often result in high costs, prolonged lead times, and limited design flexibility, this study demonstrates that FDM offers rapid prototyping capabilities, cost-effectiveness, and the ability to produce complex geometries with ease.

By comparing the performance metrics of FDM-fabricated electrodes with those produced by traditional methods and other additive manufacturing techniques like SLS and SLA, we highlight the superior attributes of FDM in terms of Material Removal Rate (MRR), surface roughness, and electrode wear.

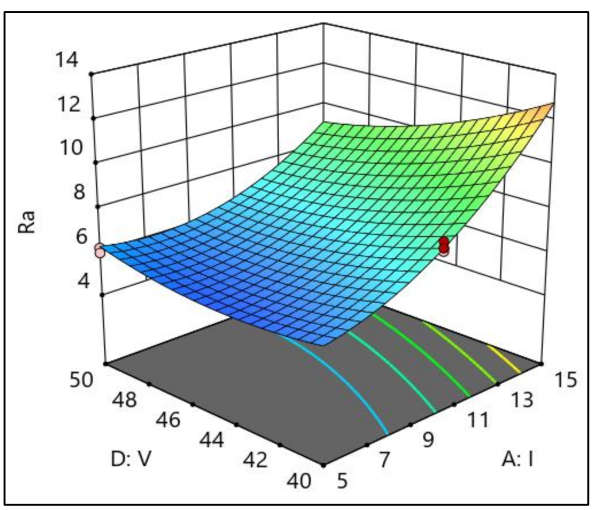
Additionally, this innovative approach to electrode metallization and optimization of EDM process parameters specifically for FDM-fabricated electrodes further underscores the novelty of the work. Through comprehensive experimental design and analysis, we reveal how the optimized EDM parameters result in improved machining performance.



(a)



(b)



(c)

Fig. 2(a) Combined effect of Ton and I, (b) Combined effect of Toff and I, and (c) Combined effect of V and I on surface roughness.

This study not only enhances the understanding of FDM technology in EDM applications but also demonstrates its practical relevance across various industries, including aerospace, automotive, and medical tooling, thus establishing a new benchmark for EDM electrode fabrication.

This research presents a significant advancement in EDM electrode fabrication by utilizing FDM technology, yielding superior results compared to state-of-the-art techniques like SLS and SLA.

By achieving precise control over electrode geometry, optimizing the metallization process through electroless plating, and meticulously tuning EDM process parameters, we observed enhanced material removal rates and improved surface finishes.

These improvements were statistically validated, demonstrating the robustness of the approach and highlighting the practical advantages of FDM-fabricated electrodes for high-precision applications in industries such as aerospace, automotive, and medical tooling.

4. Conclusion

In conclusion, the present research investigated the performance of tool electrodes manufactured through the FDM during EDM of mild steel. Through a comprehensive analysis of experimental data and statistical inference, several important findings have emerged.

Firstly, the experimental results demonstrated that the FDM-produced tool electrodes exhibited comparable performance to traditionally manufactured electrodes in terms of MRR and SR.

This suggests that FDM technology holds promise as a viable alternative for EDM electrode fabrication. Furthermore, the statistical analysis revealed significant correlations between various process parameters and machining performance.

Factors such as pulse-on-time, current, and voltage were observed to have a notable impact on MRR and SR, highlighting the importance of optimizing these parameters for enhanced machining efficiency. Additionally, the study identified the need for further research to explore advanced materials and processing techniques for FDM-generated electrodes.

By investigating alternative materials with improved electrical and thermal properties, as well as refining the FDM process parameters, it may be possible to enhance further the performance and capabilities of EDM electrodes manufactured via FDM.

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