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Integrated Analytical Modeling of Material Removal Rate and Surface Roughness in Magnetic Levitation EDM of Ti-6Al-4V

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Abstract

Electrical Discharge Machining (EDM) has emerged as a critical non-conventional machining process for difficult-to-machine materials such as Ti-6Al-4V, widely used in aerospace and biomedical applications. However, achieving an optimal balance between material removal rate (MRR) and surface roughness (Ra) remains a significant challenge due to complex thermal, plasma, and electro-physical interactions involved in the process. This study presents an integrated analytical and experimental investigation of MRR and surface roughness in Magnetic Levitation EDM of Ti-6Al-4V under varying discharge conditions. A structured experimental framework was developed by systematically varying peak current, pulse-on time, and pulse-off time while maintaining a constant servo voltage. The results reveal a direct relationship between peak current and MRR, accompanied by a deterioration in surface quality due to increased discharge energy and crater formation. A clear trade-off between machining productivity and surface integrity is observed, consistent with findings reported in advanced machining and surface enhancement processes. The proposed analytical approach, based on discharge energy principles, establishes a predictive framework for evaluating EDM performance. This study contributes toward improved parameter selection and supports multi-objective optimization of machining efficiency and surface quality in high-performance titanium alloys.

Keywords: Electrical Discharge Machining (EDM), Magnetic Levitation EDM, Material Removal Rate (MRR), Surface Roughness (Ra), Ti-6Al-4V, Analytical Modeling, Multi-objective Optimization.

1. Introduction

The increasing demand for high-performance components in aerospace, biomedical, and advanced engineering applications has intensified the need for precise machining and superior surface integrity. Surface roughness (Ra) is a critical indicator of component performance, directly influencing wear resistance, fatigue life, and functional reliability [1]. Consequently, achieving high-quality surface finish alongside efficient material removal has become a key objective in modern manufacturing processes.

Ti-6Al-4V is one of the most widely used titanium alloys due to its excellent strength-to-weight ratio, corrosion resistance, and thermal stability. However, its low thermal conductivity, high chemical reactivity, and work-hardening behavior make it difficult to machine using conventional techniques, often resulting in poor surface quality and rapid tool wear [2][3].

Electrical Discharge Machining (EDM) has emerged as an effective non-conventional machining process for such difficult-to-machine materials. The process operates through controlled electrical discharges between the tool and workpiece, leading to localized melting and vaporization of material, independent of its mechanical properties [4][5]. Advanced modeling approaches, including finite element methods and intelligent techniques, have also been explored to predict EDM performance and improve process understanding [12][13][15].

Recent developments in EDM have introduced advanced configurations such as Magnetic Levitation EDM (Maglev EDM), where the tool electrode is levitated using magnetic forces. This eliminates mechanical contact, reduces vibration, and improves discharge stability, thereby enhancing machining performance [6]. However, the complex interaction of thermal, plasma, and electromagnetic phenomena in such systems makes accurate prediction of machining responses challenging.

A major challenge in EDM is the inherent trade-off between material removal rate (MRR) and surface roughness. Higher discharge energy improves MRR but deteriorates surface quality due to the formation of larger discharge craters [7]. Similar observations have been reported in advanced machining and surface enhancement processes, where parameter optimization plays a crucial role in achieving improved surface integrity [29].

Despite extensive research, most existing models are empirical or data-driven and lack the ability to capture the combined influence of multi-physical phenomena. This highlights the need for an integrated analytical framework capable of simultaneously predicting MRR and surface roughness in advanced EDM processes such as Maglev EDM.

2. Research Gap

Despite significant advancements in Electrical Discharge Machining (EDM), most existing studies rely primarily on experimental and empirical approaches to analyze material removal rate (MRR) and surface roughness (Ra). While these approaches provide useful insights, they are often limited to specific machining conditions and lack general applicability across a wide range of process parameters [8][9].

Several experimental investigations on EDM machining of Ti-6Al-4V and similar alloys have demonstrated the influence of process parameters such as current, pulse duration, and dielectric conditions on machining performance [16][17][21]. However, these studies largely focus on experimental observations without developing generalized analytical frameworks capable of predicting machining behavior.

In addition, many studies have explored optimization of EDM parameters using statistical and hybrid techniques, highlighting the importance of process tuning for improving machining efficiency and surface quality [20][24]. Nevertheless, these approaches typically address MRR and surface roughness independently, without considering their inherent interdependence and trade-off in a unified framework.

Furthermore, conventional analytical models often neglect the combined effects of thermal energy distribution, plasma channel dynamics, and electromagnetic interactions, which play a significant role in advanced EDM configurations such as Magnetic Levitation EDM [10]. The absence of these multi-physical considerations results in incomplete representation of the machining process.

Recent studies integrating statistical and machine learning approaches have shown improved prediction capability for surface roughness; however, such integrated methodologies remain limited in advanced EDM systems and lack strong physical interpretability [30]. Additionally, emerging research directions suggest the importance of incorporating material behavior and energy interaction mechanisms for improved modeling accuracy [25][27].

Therefore, there exists a critical research gap in developing a comprehensive analytical framework that integrates multi-physical phenomena and enables simultaneous prediction of MRR and surface roughness in Magnetic Levitation EDM of Ti-6Al-4V.

3. Research Objectives

The primary objective of this study is to develop an integrated analytical model for predicting material removal rate (MRR) and surface roughness (Ra) during Magnetic Levitation EDM of Ti-6Al-4V alloy. The specific objectives of the study are as follows:

i. To analyze the effect of key EDM process parameters, including peak current, pulse-on time, and pulse-off time, on material removal rate and surface roughness.
ii. To establish a relationship between discharge energy and machining performance characteristics based on fundamental principles of thermal and electrical interactions.
iii. To investigate the trade-off between material removal rate and surface roughness for optimizing machining performance.
iv. To validate the proposed analytical model through experimental investigation under controlled machining conditions.
v. To provide a framework for selecting optimal process parameters for improved machining efficiency and surface quality.

4. Methodology

4.1 Experimental Setup

The experimental investigation was conducted to analyze material removal rate (MRR) and surface roughness (Ra) during Magnetic Levitation Electrical Discharge Machining (Maglev EDM) of Ti-6Al-4V alloy. Machining trials were performed on a high-precision Maglev EDM machine equipped with a pulse generator, dielectric circulation system, and servo control unit for maintaining a stable spark gap [26].

The workpiece material used in this study was a Ti-6Al-4V plate of dimensions 100 mm × 100 mm × 12 mm. The alloy exhibits high strength, corrosion resistance, and thermal stability, but poses machining challenges due to low thermal conductivity and high chemical reactivity [1][4].

A brass wire electrode of 0.25 mm diameter was used as the tool, while deionized water served as the dielectric medium to facilitate debris removal and maintain thermal stability during machining [28].

4.2 Machining Parameters and Design of Experiments

To evaluate the influence of process parameters on machining performance, experiments were conducted by varying peak current, pulse-on time, and pulse-off time, while maintaining a constant servo voltage of 220 V. The selected parameter range is shown below in **Table 1:**

Table 1: Machining Parameters

Block	Peak Current (A)	Pulse-on Time (μs)	Pulse-off Time (μs)	Servo Voltage (V)
1	5	100	35	220
2	10	105	40	220
3	15	110	45	220
4	20	115	50	220
5	25	120	55	220
6	30	125	60	220

The selected parameter range is presented in Table 1. The variation in discharge parameters allows systematic investigation of spark energy effects on both MRR and surface roughness [22][29].

4.3 Performance Measurement

The primary performance indicators considered in this study were Material Removal Rate (MRR) and Surface Roughness (Ra).

The material removal rate was calculated using the relation:

$$\text{MRR} = V_c \times d \times t$$

Where, V_c is the cutting speed (mm/min), d is the wire diameter (mm), and t is the thickness of the workpiece (mm) [29]. Surface roughness (Ra) was measured using a calibrated surface roughness tester. Measurements were taken at multiple locations and averaged to ensure consistency and reliability of results [23].

4.4 Analytical Modeling Approach

The analytical modeling of EDM performance was developed based on discharge energy principles. The discharge energy (E) is expressed as:

$$E = V \times I \times T_{on}$$

Where, V is the gap voltage, I is the peak current, and T_{on} is the pulse-on time. Increased discharge energy enhances material removal through melting and vaporization, thereby increasing MRR, but also results in larger discharge craters, leading to higher surface roughness [11][14].

The model incorporates fundamental principles of heat transfer and plasma channel behavior to establish a relationship between process parameters and machining responses. Such analytical approaches provide improved physical interpretability compared to purely empirical or data-driven models [15].

4.5 Experimental Validation

To validate the proposed analytical model, experimental results were compared with predicted values under identical machining conditions. The deviation between analytical and experimental outcomes was analyzed to assess model accuracy and reliability [23].

This validation ensures that the developed model can be effectively utilized for predicting machining performance and optimizing EDM parameters for Ti-6Al-4V.

5. Results and Discussion

The experimental investigation was conducted on Ti-6Al-4V using six different combinations of peak current, pulse-on time, and pulse-off time, while maintaining a constant servo voltage of 220 V. The obtained values of Material Removal Rate (MRR) and Surface Roughness (Ra) are presented in **Table 2.**

Table 2: Experimental Results

Block No.	Peak Current (A)	Pulse-on Time (µs)	Pulse-off Time (µs)	Servo Volt. (V)	MRR (mm³/ min)	Ra (µm)
1	5	100	35	220	6.01	1.12
2	10	105	40	220	6.25	1.41
3	15	110	45	220	6.43	1.76
4	20	115	50	220	6.72	1.94
5	25	120	55	220	6.94	2.38
6	30	125	60	220	7.18	2.76

5.1 Effect of Peak Current on Material Removal Rate

Figure 1 illustrates the variation of MRR with peak current. It is observed that MRR increases progressively from 6.01 mm³/min at 5 A to 7.18 mm³/min at 30 A, indicating a nearly linear relationship between peak current and material removal rate.

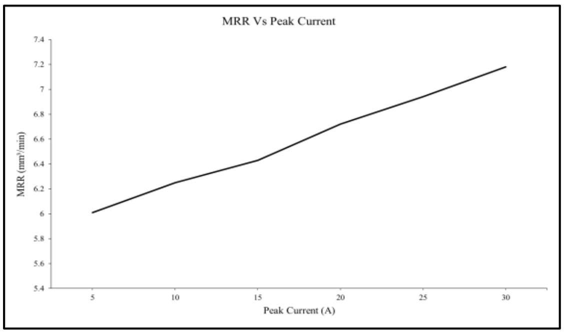

Figure 1: *MRR vs Peak Current*

This behavior is attributed to the increase in discharge energy with higher current values. In EDM, discharge energy is directly proportional to current and pulse-on time, which results in intensified thermal energy within the plasma channel. This leads to enhanced melting and vaporization of the workpiece material, thereby increasing material removal rate [11][18].

Furthermore, higher current levels generate larger plasma channels and stronger spark intensity, promoting efficient material ejection from the machining zone. While this improves productivity, it also introduces challenges related to surface integrity, as discussed in the subsequent section.

5.2 Effect of Peak Current on Surface Roughness

Figure 2 shows the influence of peak current on surface roughness (Ra). It is evident that Ra increases from 1.12 µm at 5 A to 2.76 µm at 30 A, indicating deterioration in surface quality with increasing discharge energy.

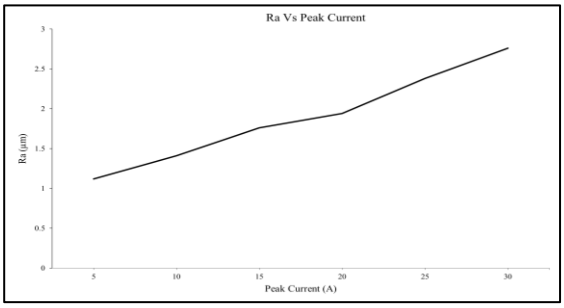

Figure 2: *Ra vs Peak Current*

This trend is primarily due to the formation of larger and deeper discharge craters at higher current values. The increased spark energy results in aggressive material removal, producing irregular surface morphology and higher roughness values [14][19].

Additionally, unstable discharge conditions and localized thermal stresses at higher currents contribute to uneven material removal and recast layer formation, further degrading surface finish. This clearly indicates that while higher current enhances MRR, it adversely affects surface quality.

5.3 Relationship Between MRR and Surface Roughness

Figure 3 presents the relationship between MRR and surface roughness, showing a clear positive correlation between the two parameters. As MRR increases from 6.01 mm³/min to 7.18 mm³/min, the corresponding Ra value increases from 1.12 µm to 2.76 µm.

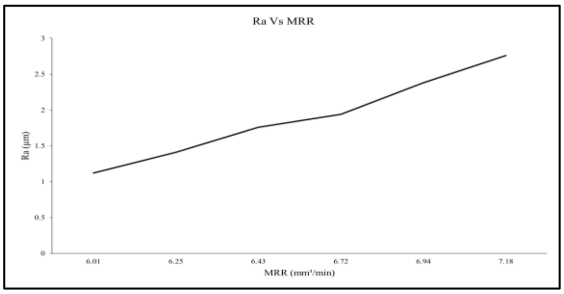

Figure 3: *Ra vs MRR*

This relationship highlights the inherent trade-off in EDM processes, where higher productivity is achieved at the expense of surface quality. The increase in discharge energy required for higher material removal results in larger crater formation, leading to rougher surfaces.

Such trade-offs are well documented in EDM and other advanced machining processes, where optimization of process parameters is necessary to balance machining efficiency and surface integrity [7]. Similar observations have also been reported in surface enhancement studies, emphasizing the importance of controlled parameter selection for achieving desired surface characteristics [29].

5.4 Discussion on Process Optimization

The results clearly indicate that peak current is a dominant factor influencing both MRR and surface roughness. While increasing current improves machining efficiency, it simultaneously degrades surface quality.

For applications requiring high dimensional accuracy and superior surface finish, lower current settings are recommended. In contrast, higher current values can be utilized for rough machining operations where productivity is prioritized.

Therefore, optimal machining performance in EDM requires a balanced selection of process parameters. The findings support the need for integrated analytical modeling and multi-objective optimization approaches to achieve an effective compromise between MRR and surface roughness.

6. Conclusion

This study presented an integrated analytical and experimental investigation of material removal rate (MRR) and surface roughness (Ra) in Magnetic Levitation Electrical Discharge Machining (Maglev EDM) of Ti-6Al-4V alloy. The results demonstrate that peak current is a dominant process parameter, significantly influencing both machining efficiency and surface quality. An increase in discharge energy leads to higher MRR due to intensified thermal erosion, but simultaneously results in degraded surface finish due to the formation of larger discharge craters.

A clear trade-off between MRR and surface roughness was established, highlighting the challenge of achieving simultaneous optimization of productivity and surface integrity. The observed trends are consistent with established EDM behavior and supported by findings in related machining and surface enhancement studies [7][29].

The proposed analytical model, based on discharge energy principles and multi-physical interactions, provides a simplified yet effective framework for predicting machining performance. Compared to purely empirical approaches, the developed model offers improved physical interpretability and supports informed parameter selection.

Experimental validation confirmed the reliability of the proposed model within the investigated parameter range, demonstrating its applicability for machining Ti-6Al-4V under controlled conditions. The outcomes of this study contribute to the advancement of predictive modeling in EDM and provide a foundation for process optimization in high-performance manufacturing applications.

Future work may focus on incorporating additional process parameters, real-time adaptive control strategies, and multi-objective optimization techniques to further enhance model accuracy and industrial applicability.

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