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# INVESTIGATION OF PROCESS PARAMETER INFLUENCE ON PERFORMANCE METRICS IN MICRO-ELECTROCHEMICAL MACHINING

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## ABSTRACT

*Micro-electrochemical machining (μ-ECM) is widely utilized for processing high-strength materials with intricate geometries, offering significant advantages in machining rates and precision. Electrochemical micromachining (EMM) has gained recognition for its numerous benefits and broad applications, establishing it as a promising technique for future micromachining endeavours. This paper focuses on optimizing process parameters for μ-ECM, specifically targeting Titanium Alloy Grade 5. Conventional machining methods often encounter difficulties when working with harder materials, making μ-ECM a preferred alternative due to its effectiveness in handling high-strength materials while ensuring efficient material removal and precise results. To explore these advantages, a series of experiments were conducted to analyze the impact of key electrochemical parameters—such as machining voltage, electrolyte concentration, and feed rate—on material removal rate (MRR) and surface roughness (SR). The study's findings provide valuable insights to enhance the efficiency of electrochemical machining systems for micromachining applications. Through this experimental investigation and detailed analysis, the study addresses various micromachining challenges, further solidifying μ-ECM as a reliable and effective choice for micromachining applications.*

## INTRODUCTION

The increasing demand for efficient space utilization and high-quality products ensures that the trend of miniaturization will continue, making micromachining technology increasingly crucial in the future. Micromachining involves the precise removal of material on a small scale, typically ranging from microns to millimeters. Advanced micromachining techniques encompass ultra-precision processes designed for small and thin workpieces, requiring the production of micro-holes, slots, and intricate surfaces in large quantities—often within a single workpiece. This is particularly significant in the electronics and computer industries.

Traditional machining methods face several challenges, including high tool wear rates, excessive heat generation at the tool-workpiece interface (which can alter material properties), and the need for high tool rigidity when machining small, deep holes or complex shapes. Additionally, the creation of three-dimensional microstructures using conventional techniques can be complex and inefficient. As a result, non-conventional machining methods are gaining prominence due to their advantages in micromachining applications.

Electrochemical machining (ECM) has witnessed renewed industrial interest over the past decade, owing to its numerous benefits, such as minimal tool wear, stress-free and smooth surface production, and the ability to machine complex shapes in electrically conductive materials, regardless of their physical and chemical properties. Micromachining typically refers to machining dimensions between 1 and 999 µm, extending to even smaller tasks that conventional methods cannot achieve. In modern electronics, chemical micromachining is widely used for applications such as manufacturing metallic parts, printed circuit boards, and semiconductor devices. When electrochemical machining is applied to micromachining for creating ultra-precision shapes, it is referred to as electrochemical micromachining (EMM).

EMM offers several advantages, including increased machining rates, enhanced precision and control, and the capability to process a wide range of materials across various applications. The selection of machining parameters in EMM plays a crucial role in achieving optimal performance. These parameters are often determined based on experience or standard values; however, such an approach does not always guarantee maximum efficiency or near-optimal performance for a specific electrochemical machining setup. Conducting an in-depth analysis of the machining process can be costly, especially for small production runs. Therefore, streamlining the selection of optimal machining parameters is essential to minimize costs and enhance economic efficiency.

Traditionally, optimization techniques for machining operations have focused on single-objective approaches, such as minimizing costs or maximizing profit. Several methods have been employed for single-objective optimization, including differential calculus, regression analysis, linear programming, geometric programming, stochastic programming, and computer simulations. While much research has centered on single-objective optimization, there have also been successful efforts in multi-objective optimization.

This paper presents a systematic study investigating the effects of three key machining parameters on the electrochemical micromachining (EMM) process. Specifically, the influence of machining voltage (V), electrolyte concentration (g/L), and feed rate (µm/s) on material removal rate (MRR) and surface finish is analyzed. The study employs Taguchi's Design of Experiments (DOE) methodology to structure the experimental design, while Grey Relational Analysis (GRA) is used to optimize the machining parameters. The findings contribute to improving the efficiency and effectiveness of electrochemical micromachining in precision manufacturing.

## LITERATURE REVIEW

Recent research has extensively applied grey relational analysis (GRA) to optimize manufacturing processes, particularly using the Taguchi orthogonal array method for refining process parameters in electrochemical micromachining (ECM) (Palani S et al., 2019) [4]. The development of electrochemical micromachining systems has been primarily driven by their applications in sectors such as automotive, aerospace, medical, and metrology (Alexander SPIESER, Atanas IVANOV, 2011) [5]. This technology has proven especially effective in precision drilling of micro-holes in hard-to-machine materials, offering significant advantages in these industries.

Each application often necessitates the design of customized workpiece clamping systems that meet specific electrical and spatial requirements to ensure optimal machining performance. Beyond drilling, ECM machines are also employed in fabricating micro-tools and micro-probes for micro-coordinate measuring machines. Recent reviews have offered valuable insights into advancements in Electrochemical Micromachining (EC-MNM) techniques, covering areas like direct writing, surface planarization, polishing, and 3D micro-nano-structured (MNS) fabrications. These reviews provide various solutions for managing confined electrochemical reactions, detailing the electrochemical principles, technical characteristics, and practical applications (Dongping Zhan et al., 2017) [6].

Further studies have examined the tooling aspects of micro-ECM technology, discussing functional design, structural elements, materials, and fabrication techniques. Such research has encouraged innovations in micro-ECM tooling, benefiting both academia and industry (Guodong et al., 2023) [7]. One notable study investigated the electrochemical micromachining of micro through-holes using a micro helical electrode combined with a jetting electrode, demonstrating a successful machining approach (Baohui Liu et al., 2020) [8].

Advancements in power supply technology have also enhanced micro-ECM capabilities. A recent innovation introduced a nanosecond pulse electrochemical micromachining power supply operating on a differential circuit. Using an STM32F103C8T6 microcontroller, this system generates high-performance rectangular waves through a Direct Digital Synthesis (DDS) device, achieving nanometer-level machining precision (Chuanjun Zhao et al., 2023) [9].

Process parameter optimization remains a key focus in electrochemical micromachining research. Studies utilizing the Taguchi and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods have optimized the machining of ground-granulated blast furnace slag (GGBS)-reinforced aluminium 6061 metal matrix composites. Parameters such as input voltage, duty cycle, electrolyte concentration, and material composition percentage were investigated to maximize material removal rate (MRR) and enhance surface finish (S. Maniraj et al., 2019) [10].

Further research has explored the electrochemical machining of 2Cr13 stainless steel, examining variables like working voltage, rotational speed, inter-electrode gap, duty cycle, and pulse frequency. Using analysis of variance (ANOVA) and GRA for optimization, the study achieved high-quality surface finishes with nearly identical material removal results across different parameter settings (Manfu Wang et al., 2023) [11].

Closed-loop electrochemical discharge machining (ECDM) has also been analyzed using response surface methodology for multi-response optimization. Key parameters such as applied voltage, electrolyte concentration, tool feed rate, and inter-electrode gap (IEG) were fine-tuned to improve micro-drilling performance (Viveksheel Rajput et al., 2022) [12]. Additionally, a study focused on optimizing the electrochemical etching process for manufacturing micro-electrodes for micro-EDM applications, achieving electrodes as small as 10 µm (Sucharita Saha et al., 2020) [13].

In the domain of brittle material machining, micro-channels have been generated using electrochemical discharge micromachining. Researchers applied an integrated mechanical system with a nonlinear artificial neural network (ANN) model to analyze machining performance effectively (Krishnendu Mandal et al., 2023) [14]. Comprehensive reviews of electric discharge machining (EDM), wire electric discharge machining (WEDM), and electrochemical machining (ECM) have further explored various optimization techniques to improve process efficiency (Nipun Gautam et al., 2022) [15].

In conclusion, electrochemical micromachining (ECM) continues to establish itself as a vital non-traditional manufacturing process, leveraging electrochemical reactions for material removal. It is particularly effective for machining hard materials like Titanium Grade 5. Ongoing research efforts aim to optimize process parameters to enhance material removal rates and achieve superior surface finishes, contributing to the overall advancement of ECM technology in precision manufacturing.

## MECM PROCESS

In this study, a rectangular titanium alloy blank measuring 6 mm in thickness and 100 mm in width was used as the specimen. The machining process was carried out using the Micro-Electrochemical Machining (MECM) technique [16].

The experiments were conducted on a "METATECH" electrochemical machine, which operates within a current range of 0-300 A and is powered by a 415 V AC supply at 50 Hz. The machine supports a tool feed rate ranging from 0.2 to 2 mm/min. During the experiment, six holes with a diameter of 5 mm were drilled into the workpiece using this setup.

For the electrolyte, a mixture of 10% NaCl and 0.2% $H_2O_2$ was used. The tool material selected for the machining process was copper. Observations from the MECM process were analyzed using Taguchi's Technique (Palani S. et al., 2019).

Further details regarding the experimental parameters, their respective levels, and the corresponding observations are presented in Tables I, II, and III.

**I. Levels and factors of parameters in the experiment**

| FACTORS | LEVEL 1 | LEVEL 2 | LEVEL 3 |
|---|---|---|---|
| Voltage (V) | 18 | 19 | 20 |
| Concentration (gm/l) | 20 | 27 | 30 |
| Feed Rate mm/min | 0.6 | 0.8 | 1 |

### II.Value Levels of experimental parameters

| Exp.No | Levels of process parameters | | |
|---|---|---|---|
| | Voltage (v) | Electrolyte Concentration (gm/Lit) | Feed Rate (mm/min) |
| **1** | 1 | 1 | 1 |
| **2** | 1 | 2 | 2 |
| **3** | 1 | 3 | 3 |
| **4** | 2 | 1 | 2 |
| **5** | 2 | 2 | 3 |
| **6** | 2 | 3 | 1 |
| **7** | 3 | 1 | 3 |
| **8** | 3 | 2 | 1 |
| **9** | 3 | 3 | 2 |

### III. Observations of MECM process based on Taguchi Orthogonal Array

| Exp.No | Levels of process parameters | | | Responses | |
|---|---|---|---|---|---|
| | Voltage (v) | Electrolyte Concentration (gm/Lit) | Feed Rate (mm/min) | MRR (gm/min) | SR (µm) |
| **1** | 18 | 20 | 0.6 | 0.006 | 0.4 |
| **2** | 18 | 27 | 0.8 | 0.009 | 0.1 |
| **3** | 18 | 30 | 1 | 0.007 | 0.3 |
| **4** | 19 | 20 | 0.8 | 0.008 | 0.2 |
| **5** | 19 | 27 | 1 | 0.008 | 0.1 |
| **6** | 19 | 30 | 0.6 | 0.007 | 0.3 |
| **7** | 20 | 20 | 1 | 0.007 | 0.2 |
| **8** | 20 | 27 | 0.6 | 0.008 | 0.3 |
| **9** | 20 | 30 | 0.8 | 0.007 | 0.3 |

## GREY RELATIONAL ANALYSIS

The Grey System Theory, introduced by Deng in 1982, has proven to be effective in addressing challenges associated with inadequate, incomplete, and uncertain information. Grey Relational Analysis (GRA), based on this theory, serves as a powerful tool for analyzing and managing the complex interrelationships among various performance characteristics [17].

In machining processes, factors such as Material Removal Rate (MRR), Tool Feed Rate, and Surface Roughness often exhibit ambiguous relationships, leading to their classification as "Grey." GRA is particularly useful in such scenarios, as it consolidates these multiple performance characteristics into a single comprehensive response, known as the Grey Relational Grade. This approach facilitates effective multi-response optimization, providing valuable insights for improving machining performance.

**i. Lower the better**

$$x^*_i(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)}$$

**ii. Higher the better**

$$x^*_i(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)}$$

**iii. A desired value**

$$x^*_i(k) = 1 - \frac{\left|x_i^{(0)}(k) - x^{(0)}\right|}{\max x_i^{(0)}(k) - x^{(0)}}$$

The grey relational coefficient could be written as:

$$\Gamma_{oi} = \frac{\Delta_{\min} + \Delta_{\max}}{\Delta' + \Delta_{\max}}$$

$$\Delta' = |1 - \Delta_{oi}|$$

The responses for Material Removal Rate (MRR) and Surface Roughness (SR) were first converted into normalized values. Following this, the grey relational coefficients for both MRR and SR were calculated. Finally, the overall grey relational grade values were determined. The normalized values and the corresponding grey relational coefficients for MRR and SR are summarized in Table IV.

**Table IV.** Normalized & GRC values for MRR and SR

| Sl. No | Normalized values for MRR | Normalized Values for SR | GRC values for MRR | GRC values for SR | Grade |
|---|---|---|---|---|---|
| **1.** | 0 | 0 | 1 | 1 | 1 |
| **2.** | 1 | 0.1 | 0.2498 | 0.7691 | 0.5095 |
| **3.** | 0.333 | 0.333 | 0.5 | 0.5 | 0.5 |
| **4.** | 0.666 | 0.666 | 0.333 | 0.333 | 0.333 |
| **5.** | 0.666 | 1 | 0.333 | 0.2498 | 0.2914 |
| **6.** | 0.333 | 0.333 | 0.5 | 0.5 | 0.5 |
| **7.** | 0.333 | 0.666 | 0.5 | 0.333 | 0.4165 |
| **8.** | 0.666 | 0.333 | 0.333 | 0.666 | 0.4995 |
| **9.** | 0.333 | 0.333 | 1 | 0.5 | 0.5095 |

## IDENTIFICATION OF SIGNIFICANT PROCESS PARAMETERS

The average grey grade was determined by calculating the mean grey relational value for each factor level within the L9 orthogonal array. The optimal parameter setting corresponds to the factor level with the highest average grey relational value.

Based on the analysis, the optimized process parameters were identified as:

**Voltage:** 18V

Electrolyte Concentration: 20 gm/l

**Feed Rate:** 0.6 mm/min

These settings resulted in a maximized material removal rate (MRR) of 0.006 gm/min and a minimized surface roughness (SR) of 0.4 µm.

## CONCLUSION

An efficient strategy was implemented to optimize the parameters for the Electrochemical Machining (ECM) of Titanium Alloy Grade 5, combining the Taguchi orthogonal array experimental design with Grey Relational Analysis (GRA).

**The experiment utilized the Taguchi orthogonal array to define the levels of key process parameters, including:**

Applied Voltage

Electrolyte Concentration

Feed Rate

After conducting the machining process, the Material Removal Rate (MRR) and Surface Roughness (SR) were measured. A comprehensive analysis was then performed to identify the critical process parameters, ensuring enhanced machining performance.

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