



Low-Current Wire EDM Optimization for Precision Micro-Components

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Abstract

The article is dedicated to the optimization of low-current wire electrical discharge machining for the production of precision micro-components under conditions of constrained thermal input. The relevance is determined by the increasing demand for high-accuracy elements in aerospace, medical, and micro-engineering applications, where conventional machining regimes introduce excessive thermal damage. The work describes the transformation of erosion mechanisms under reduced discharge energy and studies the interaction between electrical parameters, dielectric behavior, and material response. Special attention is paid to the restructuring of the discharge process, where stability becomes dependent on synchronized parameter control rather than energy intensity. The work sets itself a task to explain how low-current regimes reorganize the machining system and to identify the conditions under which dimensional accuracy and surface integrity are improved. Analytical synthesis of recent studies is used to solve this problem. The conclusion describes the transition of WEDM from a high-energy removal process to a controlled sequence of micro-scale interactions. The article will be useful for engineers and researchers working with precision manufacturing and advanced materials processing.

Keywords: Low-Current Machining, Micro-Components, Surface Integrity, Discharge Stability, Process Optimization.

INTRODUCTION

Precision micro-components increasingly define the performance limits of modern engineering systems. Their fabrication requires not only geometric accuracy but also controlled surface morphology and repeatable process behavior. Wire electrical discharge machining occupies a central position in this domain due to its ability to process hard and difficult-to-machine materials without mechanical contact. The absence of cutting forces eliminates deformation associated with conventional machining. Yet, this advantage becomes conditional when the process is transferred to micro-scale geometries.

Thermal input begins to dominate. Even moderate discharge energies generate localized melting zones that exceed acceptable limits for thin or delicate structures. The resulting recast layer, microcracks, and dimensional deviations are not incidental effects. They reflect the inherent structure of high-energy discharge regimes. The machining system operates through intensive thermal pulses that prioritize removal efficiency over control.

The aim of the study is to theoretically substantiate the transformation of the wire EDM process under low-current

conditions and to identify the system-level interactions that determine machining stability and quality.

To reach this purpose, three research objectives are formulated. First, to analyze how reduction of discharge energy alters the internal mechanisms of material removal and surface formation. Second, to identify the interaction between electrical, mechanical, and fluid parameters that governs process stability in low-energy conditions. Third, to evaluate how these interactions influence machining outcomes in terms of roughness, recast layer formation, and repeatability.

The hypothesis assumes that machining performance in low-current WEDM can be improved when the process is controlled as a system of interdependent parameters rather than independently optimized variables.

The novelty lies in the reinterpretation of low-current WEDM not as a parameter adjustment strategy but as a transition to a different operational regime, where discharge behavior, dielectric dynamics, and material response form a tightly interconnected structure. Existing studies often examine these elements separately, while their interdependence remains insufficiently explained. The present work addresses this gap.

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METHODS AND MATERIALS

The literature base was assembled through targeted retrieval from international scientific databases, including Scopus, Web of Science, and IEEE Xplore, with a focus on publications from the last five years. The search combined keyword clusters related to electrical discharge machining, micro-scale processing, and parameter optimization using logical operators to connect process variables and performance indicators. Approximately forty sources were initially identified and subsequently narrowed to a focused set of studies through title, abstract, and full-text evaluation.

Selection emphasized works that described not only process parameters but their interaction within the machining system. Analytical attention was directed toward how these components influence surface integrity, dimensional accuracy, and process stability.

The selected studies revealed a heterogeneous landscape. Some focused on experimental parameter optimization, others on microstructural analysis or modeling approaches. Despite this diversity, common structural patterns emerged: the dependence of erosion behavior on energy distribution, the critical role of dielectric flushing in maintaining discharge continuity, and the sensitivity of the process to material properties.

At the same time, comparison of these works exposed a consistent limitation. Electrical, thermal, and fluid processes are frequently analyzed in isolation, while their combined influence on machining stability remains only partially described. This fragmentation restricts the ability to explain why optimal parameter combinations are confined to narrow operational windows.

The analytical synthesis therefore proceeds by interpreting the machining process as an integrated system of interacting subsystems. This approach allows the identification of internal dependencies that are not explicitly addressed in individual studies and provides the basis for the present reinterpretation of low-current WEDM.

RESULTS

Energy redistribution at reduced discharge levels produces a qualitatively different erosion regime, where the plasma channel no longer acts as a high-intensity melting source but operates within a constrained thermal envelope. Under such conditions, the spatial extent of molten material contracts, and the resulting craters exhibit reduced diameter and depth, which alters the topology of the machined surface. Instead of irregular overlapping features, the surface develops through discrete, weakly interacting erosion events. This transition becomes particularly evident in micro-WEDM operations, where surface roughness values can decrease from 2.79 μm to 0.12 μm when pulse parameters are reduced and discharge energy is controlled (Sarala Rubi et al., 2024). The mechanism behind this reduction lies in the limitation of

secondary discharges, which are otherwise responsible for surface irregularities through repeated thermal cycling.

The erosion-removal cycle becomes increasingly dependent on dielectric behavior as energy input decreases. At lower discharge intensities, debris evacuation defines whether subsequent discharges occur in a clean or contaminated gap. Experimental observations under 8 A peak current, 0.45 μs pulse-on time, and 45 μs pulse-off time show that stable erosion can be maintained only when the dielectric effectively removes molten particles between pulses (Goutham et al., 2020). When the dielectric medium shifts from deionized water to an oil-wax-paraffin composition, the material removal rate increases by 0.18–33.97%, while surface roughness rises by 2.15–36.86%, indicating that higher viscosity fluids alter both energy dissipation and flushing dynamics (Goutham et al., 2020). The process therefore reorganizes around fluid-plasma interaction rather than purely electrical input.

The structure of the recast layer reflects the same transition toward controlled thermal exposure. Reduced peak current limits the volume of molten material, which directly constrains the thickness of the resolidified layer. Microstructural analysis demonstrates that peak current and pulse-on time remain the dominant variables governing recast layer formation, while pulse-off time contributes minimally to its thickness (Sarkar et al., 2024; González-Rojas et al., 2024). This indicates that solidification processes are primarily driven by the magnitude of thermal input rather than cooling duration. At lower energy levels, the recast layer becomes thinner and more homogeneous, with fewer microcracks and reduced internal stress gradients.

Dimensional accuracy emerges as a consequence of both electrical and mechanical stabilization. Kerf width decreases as pulse-on time is shortened, since the plasma channel contracts and lateral erosion is reduced.

Material removal rate does not simply decline with decreasing current. Instead, it reflects a balance between discharge frequency and debris evacuation. Increasing pulse-on time or current enlarges crater volume and accelerates removal, yet this is accompanied by surface degradation and instability. Conversely, reducing these parameters lowers removal rate but enhances surface integrity. In composite machining environments, optimized parameter sets demonstrate that peak current remains the dominant factor influencing material removal rate, while flushing pressure has the strongest effect on surface roughness (Madhavarao et al., 2024). Under Taguchi-based optimization, parameter combinations such as TON = 100, PF = 70 kg/cm^2 , and IP = 140 A produce improved surface characteristics, whereas maximum material removal rate is achieved at TON = 105 μs with the same flushing pressure and current level (Madhavarao et al., 2024). These results indicate that optimal regimes are confined to narrow parameter intervals rather than broad operating ranges.

Material structure introduces an additional layer of interaction. In hybrid metal matrix composites based on AA7475, reinforcement distribution affects both erosion stability and resulting surface characteristics. Compositions containing 4 wt.% ZrO₂ and 2 wt.% graphite exhibit an ultimate tensile strength of 320 N/mm² and hardness of 100.6, reflecting a more uniform internal structure that redistributes thermal stress during discharge events (Madhavarao et al., 2024). This redistribution reduces localized overheating and contributes to more consistent crater formation. The machining response is therefore partially governed by the internal architecture of the material, not solely by external process parameters.

Surface generation in EDM systems follows a thermally driven mechanism where localized melting, vaporization, and rapid quenching define the final morphology. At reduced energy levels, the proportion of vaporization relative to melting increases, which alters the morphology of the eroded surface and reduces the formation of resolidified debris (Nafi and Jahan, 2023). This shift explains the observed improvement in surface integrity and reduction in micro-defects. At the same time, the use of coated or composite wires modifies heat transfer within the discharge zone, enabling more stable energy distribution and reducing wire breakage risks (Sarala Rubi et al., 2024; Straka and Čorný, 2024; Ablyaz et al., 2021).

The role of dielectric and electrode materials becomes particularly pronounced when machining advanced materials such as silicon carbide composites. Variations in thermal conductivity and electrical resistivity alter the discharge channel behavior, requiring adaptive parameter control. In such systems, the machining process becomes sensitive to micro-scale variations in material properties, which can destabilize the discharge if not compensated through parameter adjustment (Fard et al., 2025). This sensitivity reinforces the need for coordinated control of electrical, mechanical, and fluid parameters.

Predictive modeling introduces a different layer of control by capturing non-linear relationships between process

variables and output characteristics. Machine learning approaches applied to micro-EDM processes demonstrate that interactions between current, voltage, and pulse duration can be modeled to predict surface roughness and material removal rate with high accuracy (Ali et al., 2025). These models do not change the physical mechanism of erosion but restructure how parameter space is explored, reducing reliance on trial-based optimization.

Several limitations should be acknowledged. Variations in dielectric composition, material systems, and experimental configurations restrict direct comparison of quantitative results. Composite materials introduce heterogeneity that alters local discharge behavior, complicating generalization. Differences in measurement approaches for surface roughness and recast layer thickness further limit cross-study consistency.

Low-current WEDM reshapes the machining system at a structural level. Energy input becomes a controlled variable rather than a maximizing factor. Material removal evolves into a sequence of regulated micro-events. Stability replaces intensity as the dominant condition of operation.

DISCUSSION

The transition to low-current regimes alters not only the magnitude of thermal input but the internal organization of the machining system itself. Electrical discharge machining ceases to behave as a purely energy-dominated removal process and begins to operate as a coordinated interaction between discharge generation, dielectric renewal, and localized material response. The observed reduction in surface roughness and recast layer thickness reflects this reconfiguration. Smaller discharge energies generate shorter-lived plasma channels, which restrict the volume of molten material and limit lateral heat propagation. As a result, surface formation becomes governed by a sequence of discrete micro-events rather than overlapping thermal cycles. The machining system stabilizes around repetition instead of intensity. The systematization of approaches is presented below (Table 1).

Table 1. Structural components of low-current WEDM process organization (compiled by the author based on Sarala Rubi et al., 2024; Madhavarao et al., 2024; Nafi and Jahan, 2023)

Process Layer	Functional Role	Interaction Mechanism	Effect on Machining Outcome
Discharge Generation System	Controls energy release per pulse	Regulates plasma channel formation	Defines crater size and thermal footprint
Dielectric Circulation System	Removes debris and cools gap	Maintains electrical insulation between pulses	Stabilizes discharge sequence
Material Response Layer	Absorbs and redistributes thermal energy	Governs melting, vaporization, and solidification	Determines surface integrity
Wire Electrode System	Transmits energy and maintains geometry	Influences spark gap and trajectory stability	Affects dimensional accuracy
Control Parameter Layer	Synchronizes timing and intensity	Couples Ton, Toff, current, flushing	Defines process stability window

This restructuring becomes more pronounced when considering how debris is processed within the inter-electrode gap. At conventional energy levels, debris accumulation is partially compensated by high-energy discharges capable of re-melting residual material. In low-current conditions, such compensation is no longer available. The system becomes dependent on the efficiency of dielectric flushing to maintain discharge continuity. When debris evacuation is

insufficient, conductive bridges form prematurely, leading to unstable discharges and local short-circuiting. Process stability weakens. In contrast, effective flushing restores gap conditions between pulses, allowing each discharge to occur under controlled electrical conditions. The system begins to resemble a regulated cycle rather than a stochastic sequence of events. The systematization of approaches is presented below (Figure 1).

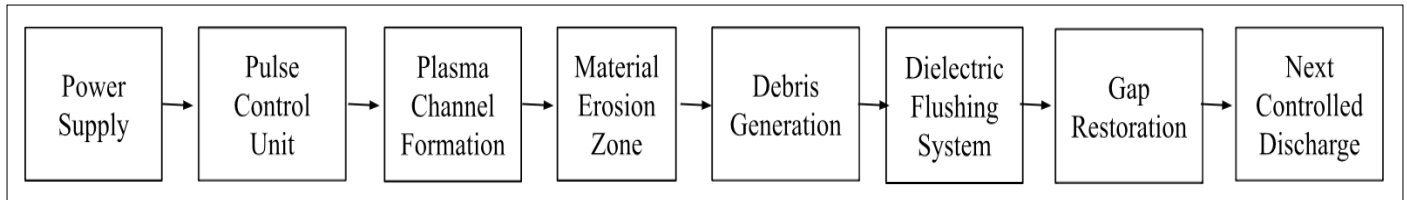


Figure 1. Operational scheme of low-current WEDM process interaction (compiled by the author based on Goutham et al., 2020; Sarkar et al., 2024; Straka and Čorný, 2024)

Parameter interactions reinforce this interpretation. Pulse-on time, peak current, and flushing pressure do not operate independently; they form a tightly coupled control structure. Short pulse durations reduce crater size but require sufficient off-time to allow dielectric recovery. Peak current defines the energy envelope, yet its effect depends on how quickly the gap is cleared of debris. Flushing pressure governs this clearing process, effectively determining whether reduced energy leads to precision or instability. In practice, optimal machining occurs within a narrow parameter window where these variables are balanced. Outside this window, the system either loses efficiency or destabilizes.

The role of material structure introduces an additional layer of complexity. Composite systems, particularly those reinforced with ceramic particles, redistribute thermal energy differently from homogeneous alloys. Reinforcement particles interrupt heat flow, creating localized gradients that influence how material melts and solidifies. When reinforcement distribution is uniform, thermal energy spreads more evenly, reducing localized overheating and improving surface consistency. When distribution is uneven, discharge behavior becomes irregular, leading to localized defects. The machining response is not solely determined by process parameters. It is co-defined by material architecture.

Surface integrity follows from this interaction between energy input and material response. The recast layer forms through rapid solidification of molten material, and its characteristics depend on both the volume of melt and the cooling dynamics. Reduced discharge energy limits melt volume, while controlled dielectric flow enhances cooling uniformity. Together, these factors suppress microcrack formation and reduce residual stresses. However, the system remains sensitive to parameter drift. Slight increases in pulse duration or current can reintroduce thermal gradients sufficient to generate structural defects. Stability requires continuous control. The systematization of approaches is presented below (Figure 2).

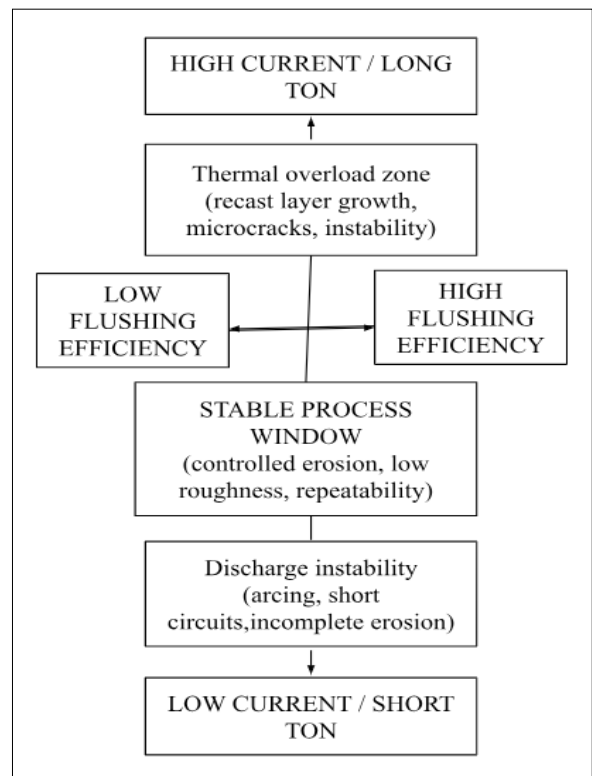


Figure 2. Stability envelope of low-current WEDM process depending on parameter interaction (compiled by the author based on Sarala Rubi et al., 2024; Madhavarao et al., 2024; Sarkar et al., 2024)

These observations align with earlier investigations into WEDM behavior, where discharge energy has consistently been identified as a primary determinant of both material removal rate and surface quality. At the same time, prior work has often treated process parameters as independent variables, optimizing them through statistical methods without fully resolving their interaction mechanisms. The present analytical synthesis suggests that such independence is only apparent at higher energy levels. Under low-current conditions, parameter coupling becomes dominant, and isolated optimization loses effectiveness. The process must be interpreted as an integrated system.

Adaptive control strategies developed in earlier studies reflect an implicit recognition of this complexity. Fuzzy logic systems, neural networks, and multi-objective optimization frameworks attempt to capture non-linear relationships between parameters and outputs. Their effectiveness lies not in replacing physical understanding but in navigating a parameter space where interactions are too complex for linear models. Low-current regimes amplify this complexity. Small variations in input produce disproportionate changes in output. Predictive modeling becomes a necessity rather than an enhancement.

At the same time, limitations inherent to the analytical basis of this discussion must be acknowledged. The analysis relies on previously published studies, which vary in experimental design, material systems, and measurement techniques. Differences in dielectric composition, electrode materials, and machine configurations restrict direct comparability of numerical results. Composite materials introduce heterogeneity that alters local discharge behavior, complicating generalization across different material classes. Variations in how surface roughness, recast layer thickness, and material removal rate are measured further limit cross-study consistency.

Another constraint emerges from the absence of unified experimental conditions for micro-scale machining. Many studies focus on specific materials or parameter ranges, making it difficult to construct a fully continuous representation of system behavior across all regimes. In addition, the interaction between mechanical factors such as wire tension and electrical parameters remains insufficiently quantified, despite its influence on machining accuracy. The system is only partially observed.

What becomes evident through this discussion is not a simple improvement in machining performance, but a shift in how the process operates. Low-current WEDM does not merely reduce thermal damage. It reorganizes the machining environment into a tightly coupled system where electrical, thermal, and fluid interactions must remain synchronized. Precision emerges from coordination. Not from force.

CONCLUSION

Reduction of discharge energy changes the internal structure of the machining process rather than simply modifying its intensity. The analysis shows that material removal becomes governed by coordinated micro-scale interactions, where plasma formation, dielectric renewal, and material response operate as a unified system.

The first research objective is achieved through identification of how reduced energy alters crater formation and limits thermal propagation, leading to improved surface integrity. The second objective is addressed by demonstrating that process stability depends on the coupling between pulse parameters, flushing conditions, and gap dynamics. The third objective is fulfilled through explanation of how these

interactions define dimensional accuracy and repeatability within a constrained parameter window.

The hypothesis is confirmed. Low-current regimes reorganize the machining system into a structure where parameter interdependence replaces independent optimization.

Wire EDM in this configuration no longer operates as a high-energy removal process. It functions as a controlled system of synchronized interactions. The study contributes to the theoretical understanding of micro-WEDM by redefining it as a system-controlled process rather than a purely energy-driven mechanism. The results can be applied to optimize machining parameters in precision manufacturing, particularly in applications requiring minimal thermal impact and high surface integrity.

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