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Balancing Productivity and Sustainability in EDM: A Comprehensive Analysis of Energy Consumption and Electrode Degradation

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Abstract: Die-sinking Electrical Discharge Machining (EDM) is a manufacturing process for fabricating complex geometries in challenging applications. However, its energy-intensive nature and complex parameter interactions pose challenges in balancing productivity, sustainability, and electrode wear. This study presents a comprehensive analysis of energy consumption and electrode degradation in EDM. Utilizing an advanced experimental setup with real-time energy monitoring, this study investigated the trade-off between machining parameters, energy efficiency, and electrode wear. The study employed a simple and standardized electrode geometry and varied EDM parameters, such as discharge current and pulse duration. The obtained results clearly demonstrated that optimizing EDM machining parameters, particularly discharge current, significantly influenced machining efficiency and electrode wear. Specifically, employing high-current settings of 140 A substantially reduced the total machining time from approximately 33 h (at conservative settings of 40 A) down to around 3.5 h, achieving nearly a tenfold improvement. Moreover, it also led to a reduction in specific energy consumption (SEC), decreasing from 0.81 Wh/mm^3 at the low current (40 A) to 0.19 Wh/mm^3 at the higher current (140 A), underscoring a definitive inverse relationship between discharge current and energy consumption. The study outcomes provide practical guidelines for enhancing the operational efficiency and sustainability of EDM in advanced manufacturing sectors.

Keywords: electrical discharge machining (EDM); energy consumption; electrode degradation; machining parameters; material removal rate (MRR); specific energy consumption (SEC)

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1. Introduction

Die-sinking Electrical Discharge Machining (EDM) is widely acknowledged as an advanced and key manufacturing process, particularly for fabricating complex geometries with materials that are traditionally difficult to machine. This technique operates through a controlled sequence of electrical discharges, facilitated by a dielectric fluid, with the aim of achieving a very high surface finish [1]. As presented in Figure 1, the erosion process replicates the contour of the electrode. This achieves high fidelity in the reproduction of complex shapes, a feature that is critically important for high-precision sectors, such as aerospace, automotive, and tooling, where conventional machining methods are often inadequate [2,3]. Products produced using such techniques are molds and dies or fully machined impellers for the energy sector. Despite its significant advantages, die-sinking EDM faces challenges owing to its inherent energy-intensive nature and the complexities associated with its operational parameters. Key machining factors—namely, electrical current, applied voltage, and pulse duration—exhibit a multifaceted correlation that directly affects the material removal rate (MRR), overall machining time, and surface integrity of the workpiece [4]. Consequently, achieving optimal process performance requires the fine-tuning of these parameters to enhance productivity while concurrently mitigating environmental and economic costs [5].

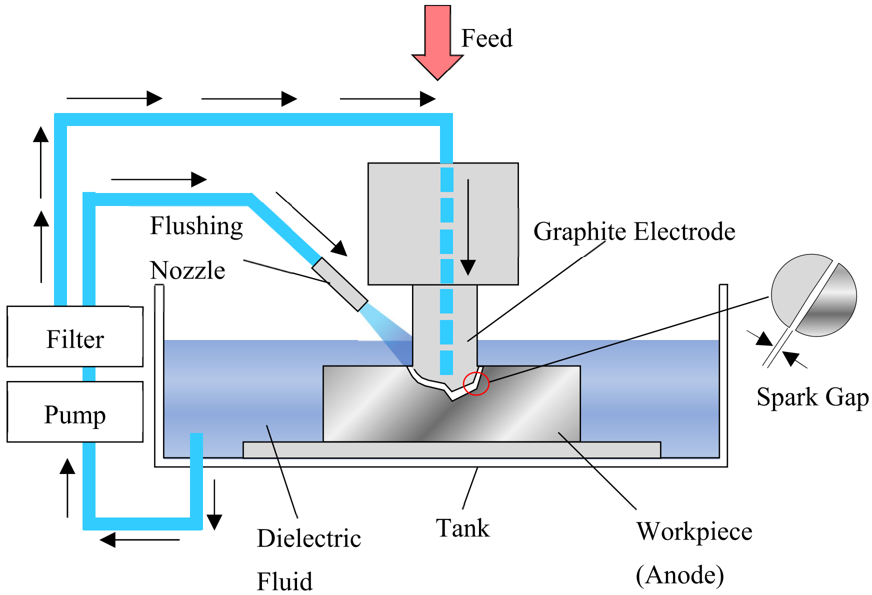


Figure 1. Schematic diagram of die-sinking EDM.

The motivation for investigating energy consumption and electrode degradation in EDM arises primarily from the significant operational costs and environmental concerns associated with energy-intensive manufacturing processes, as well as the economic impact of frequent electrode replacement or reconditioning. With industries increasingly focusing on sustainability and efficient resource utilization, understanding the interplay between EDM parameters, energy usage, and electrode wear becomes essential to improve machining efficiency, reduce manufacturing costs, and minimize the environmental footprint.

In response to these challenges, considerable research efforts have been directed toward developing advanced solutions. Innovations have focused on designing and implementing high-durability electrode materials and geometries that significantly enhance machining precision and efficiency [6]. Simultaneously, the energy consumption of die-sinking EDM machines has emerged as a critical metric influenced by multiple factors, including the nature of the discharge process, auxiliary systems, and machine design. Therefore, the accurate measurement and control of energy consumption are essential not only for improving machining efficiency but also for reducing operational costs and minimizing environmental impacts. This growing emphasis on the environmental footprint of manufacturing processes has led to the development of energetic models that provide a robust framework for evaluating overall energy utilization in machining processes. These models systematically analyze the power absorbed by all the machine subsystems. They employ both system sizing (e.g., subsystem nominal power) and direct measurement techniques to accurately determine total power consumption during machining operations [3,6,7].

This quantitative approach facilitates a comprehensive understanding of energy distribution throughout the process, enabling precise assessments that are critical for optimizing the process performance. Moreover, by incorporating the energy demands of auxiliary systems—such as chillers, which often impose a significant energy burden on micro-EDM machines—these models empower manufacturers to identify and target specific areas for energy consumption optimization [8,9]. In an automotive case study, the researchers used line balancing to reduce waiting time and improve assembly efficiency. While effective for task allocation in linear workflows, their study did not address machining systems. This research adapts lean principles to EDM, where optimization must also consider thermal effects, energy demand, and tool wear [10]. Complementing these energetic models, discharge-based models offer a focused perspective on the dynamics of the electrical discharge process by correlating essential machining parameters—such as current, voltage, and pulse timing—with the material removal rate (MRR), thus providing estimates of the energy required for effective material removal [4,6]. This study successfully applied Manufacturing Cycle Efficiency (MCE) to reduce time wastage and improve productivity in automotive wiring harness assembly. However, their work focused on mechanical operations without considering energy-intensive processes. The present study extends MCE analysis to EDM, integrating energy consumption and electrode wear—factors critical for optimizing subtractive manufacturing systems [11]. This targeted analysis enhances the ability to fine-tune machining operations by directly linking the process parameters with the energy efficiency outcomes. Further insights are gained by isolating the energy consumed during active discharge from that used by auxiliary systems, which yields valuable data to assess and improve the intrinsic performance of the process itself [12].

Advancements in measurement techniques have led to the integration of real-time monitoring systems into modern machining environments. These systems combine advanced sensors with sophisticated data acquisition techniques to continuously track energy consumption across all machine subsystems, enabling the prompt detection of inefficiencies and allowing operators to dynamically adjust process parameters to maintain optimal energy use [7,8]. In addition to these systems, acoustic emission (AE) monitoring techniques have emerged as non-invasive methods for assessing energy fluxes during machining operations. By analyzing the vibroacoustic signals generated during material removal, AE monitoring provides a real-time evaluation of the energy expended, ensuring that the process maintains optimal performance without disrupting the operational workflow [13].

An important concept in the evaluation of energy efficiency is the specific energy consumption (SEC) metric, which is the energy consumed to remove a standard volume of material, crucial for assessing the overall efficiency of an EDM process. Hence, the SEC provides a valuable comparative framework for evaluating the performance of different machining setups. This metric is particularly beneficial for contrasting the energy performance of conventional EDM technologies with that of more advanced systems, thereby driving further process improvements and optimization [14,15].

At the heart of these energy considerations lies the complex relationship between the material removal rate (MRR) and machining parameters in die-sinking EDM, a relationship characterized by nonlinear interactions and trade-offs. A thorough understanding of these correlations is critical for optimizing the process to achieve high productivity and energy efficiency while maintaining surface quality. In advanced machining processes, several key electrical parameters play a decisive role in influencing both the MRR and overall process performance. One of the most influential of these parameters is the peak current (I_p)—a peak in current intensity that amplifies the energy delivered during each electrical discharge, thereby accelerating the material removal process. However, this benefit is counterbalanced by elevated thermal loads, which can adversely affect the surface finish and accelerate electrode wear [5,16]. This relationship between current and MRR is particularly significant in applications such as mold making and aerospace manufacturing, where the demand for rapid material removal often takes precedence over the need for a high-quality surface finish [17].

Complementing the role of current, voltage (V_x) is fundamental in regulating the energy transfer during each discharge. Maintaining an optimal voltage level is essential for ensuring stable sparking conditions that promote uniform material erosion; conversely, excessive voltage can lead to arcing and unstable discharge conditions, which detrimentally affect both the MRR and the quality of the machined surface [17,18]. Furthermore, the pulse timing parameters, specifically the pulse-on time (T_{on}) and pulse-off time (T_{off}), further refine the efficiency of material removal. Extended pulse-on times facilitate greater energy transfer per discharge, thereby enhancing the MRR, but the increased energy transfer also elevates the risk of thermal damage to both the workpiece and the electrode, potentially compromising surface integrity [16]. In contrast, shorter pulse durations focus energy delivery more precisely, reducing the heat-affected zones, although this approach may limit the overall material removal rate. Additionally, the pulse-off time is critical, as it governs the recovery period for the dielectric fluid and ensures the effective removal of debris; insufficient off time may result in erratic discharges, diminishing process efficiency and intensifying electrode wear [17].

Ultimately, the intricate correlation between these electrical parameters underscores the necessity for a holistic optimization strategy, where adjustments made to enhance one parameter often require compensatory modifications in others to sustain process stability and efficiency. For instance, increasing the current to boost the MRR may necessitate a reduction in pulse duration or voltage to mitigate the risks associated with thermal damage and excessive electrode wear [19]. Through such a balanced and integrated approach, manufacturers can effectively tailor die-sinking EDM processes to meet specific operational demands while achieving high levels of precision and energy efficiency.

Numerous external studies have explored the energy aspects of EDM, such as energetic modeling and parameter optimization, to improve efficiency and electrode lifespan. However, these studies have often isolated theoretical modeling from real-world applications, rarely integrating real-time monitoring data or considering the compounded impact of auxiliary machine systems. The current research bridges these critical gaps by conducting empirical investigations that combine advanced real-time monitoring systems with systematic experimental analyses. This integrated approach not only expands upon previous external findings but also provides practical insights into parameter optimization, specifically addressing simultaneous considerations of machining productivity, energy efficiency, and electrode wear. A key novelty is the use of a simplified, standardized graphite electrode across all trials, which ensures consistent volume removal and enables accurate comparisons of specific energy consumption under varying process settings. This allows for a deeper understanding of how parameter changes impact both energy use and electrode degradation—delivering actionable insights for optimizing EDM processes in both performance and sustainability.

Therefore, the primary objective of this research is to empirically quantify the effects of key EDM machining parameters—particularly discharge current and pulse duration—on energy consumption, machining efficiency, and electrode wear. It is hypothesized that optimized combinations of these parameters significantly lower specific energy consumption (SEC) and machining time without causing unacceptable electrode degradation. The experimental validation of these hypotheses, detailed in the following section, directly addresses the limitations identified in prior research.

2. Materials and Methods

In this study, an Agie Charmilles FORM 3000 VHP, manufactured by GF machining solutions, Milan Italy, presented in Figure 2, was used to conduct the experiments and collect data in a plant owned by Baker Hughes, a company that operates worldwide in the energy sector. The machine has been equipped with a Modbus-capable energy meter manufactured by Ceam Group, Empoli, Italy, used for acquiring energy consumption data. The current was recorded using Class 1, 100 A:5 A open-core clamp-on current transformers. The open-core design enables easy installation by clamping around the power cables without the need for disconnection or interruption of the power supply. The schematics in Figure 3 shows the data collection process using the RS485 Modbus protocol wirelessly over WiFi.

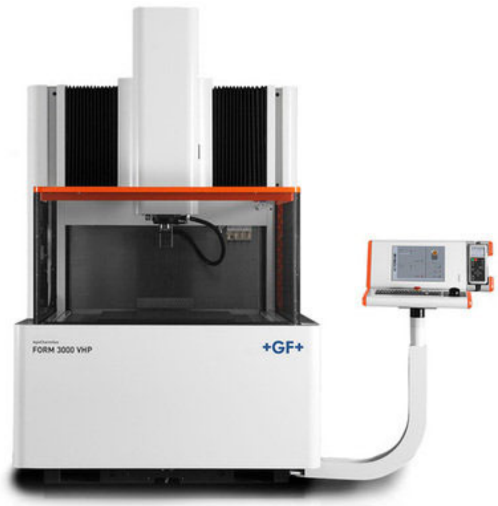


Figure 2. Agie Charmilles Form 3000 VHP EDM Machine.

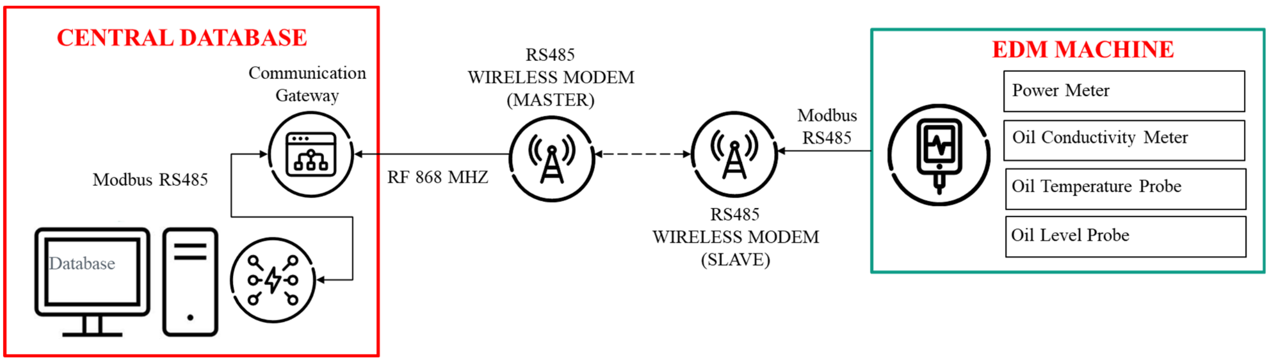


Figure 3. Data acquisition setup schematics.

From the schematics, it can be seen that the machine, as shown, is fitted with a power meter, an oil conductivity meter, an oil temperature probe, and an oil level probe. However, for this study, we will only discuss the results from the power meter and PLC data. This information is first sent to a WiFi modem using the RS485 protocol, which is then transmitted to another control or master WiFi modem that receives it and sends it to a Communication Gateway. The Communication Gateway is located in the central database cluster. This cluster consists of a locally hosted database that stores all the information coming from the production machines. This information is useful for controlling the overall performance of all the plants and comparing the relative efficiency of the installed machines.

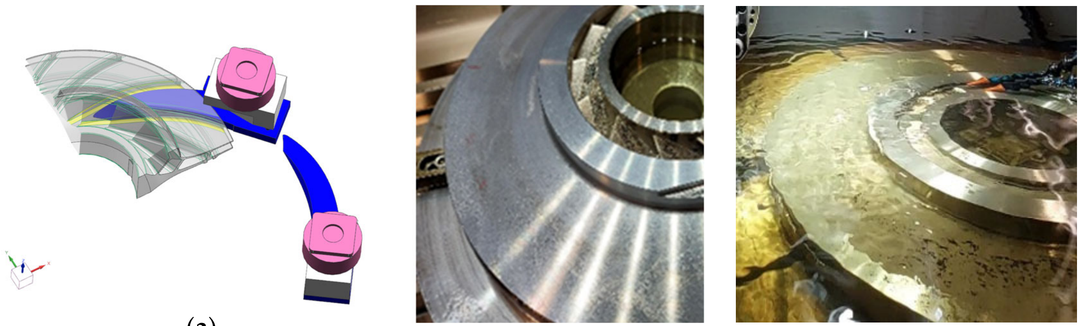
Although the data acquisition system employed high-resolution power meters and the real-time monitoring of auxiliary systems, several sources of error may still affect the measurements. Potential uncertainties arise from the dynamic fluctuations in discharge pulses, minor delays in power signal synchronization, and thermal drift in sensor calibration over extended machining cycles. Additionally, the indirect measurement of SEC relies on the assumption of a constant material removal volume per trial, which may be affected by unmeasured electrode micro-chipping or flushing inefficiencies. While these factors were minimized through repeated trials and equipment calibration, they represent inherent limitations in high-resolution energy analysis in EDM.

In this study, three sets of experiments were performed to determine the optimal setup for the process. The setup, analysis, and results are presented in the following sections.

3. Experiment and Setup

3.1. Preliminary Experiment

The first experiment involved an in-depth analysis of the energy consumption characteristics of the target EDM machine, conducted via a series of cutting tests employing production electrodes. This phase of the study focused on the machining process during the roughing stage of impeller vane development, with details provided in Figure 4.



(**a**) (**b**) (**c**)

Figure 4. (**a**) Illustration of the impeller and electrode, (**b**) impeller stock, (**c**) impeller in an EDM machine.

A single-electrode geometry featuring an impeller vane was employed, and four different combinations of parameters were tested. The dielectric fluid used in all the experiments was standard-grade kerosene, which is the default working fluid in the production line. Kerosene is widely used in industrial EDM applications due to its high dielectric strength, moderate viscosity, and effective cooling and flushing characteristics. The machine's internal system maintained a continuous circulation of the fluid, ensuring stable flushing during machining. Although the exact flow rate is not directly adjustable or specified by the manufacturer, it is automatically controlled to meet the default preset conditions for each selected machining mode. The discharge current values selected for this study (40 A, 80 A, 100 A, and 140 A) correspond to the available preset configurations provided by the EDM machine manufacturer. These presets are pre-programmed into the machine and represent standard industrial settings optimized by the manufacturer for different machining objectives. Importantly, the only variable intentionally modified in this study was the discharge current; all other parameters—including pulse duration, duty cycle, and flushing conditions—were left at their default values as defined by the machine's internal control logic. The two preset types—High Material Removal Rate (High MRR) and Low Tool Wear—are built-in technology options that cannot be manually altered in terms of their internal settings, ensuring consistency and repeatability. This approach reflects realistic industrial usage scenarios, where operators rely on certified machine presets to balance performance and tool wear without manually tuning every discharge parameter. The preset and pulse current settings used in this experiment are given in Tables 1 and 2.

Table 1. Types of test cases performed.

Test N°	Ampere	Preset Type
1	80	2 (Low Tool Wear)
2	100	1 (High M.R.R.)
3	100	2 (Low Tool Wear)
4	80	1 (High M.R.R.)

Table 2. Preset specifications.

Preset 1 High MRR			Preset 2 Low Tool Wear		
Specifications	**Values**	**Units**	**Specifications**	**Values**	**Units**
T: Pulse-on time	154	µs	T: Pulse-on time	422	µs
P: Pulse-off time	87	µs	P: Pulse-off time	87	µs
I: Discharge current	user-defined	amps	I: Discharge current	user-defined	amps
U: Voltage	100	volts	U: Voltage	100	volts

Before the four tests from Table 1 were performed, the base energy consumption of the EDM machine while idle was measured, and after each test, the total time, mean machining power, total energy, energy consumed by the refrigeration unit, and fixed spark current were recorded. The plots for total system power vs. time are shown in Figures 5–8 for all four test cases. These plots are raw unlabeled data; hence, subsystem differences cannot be identified in these plots.

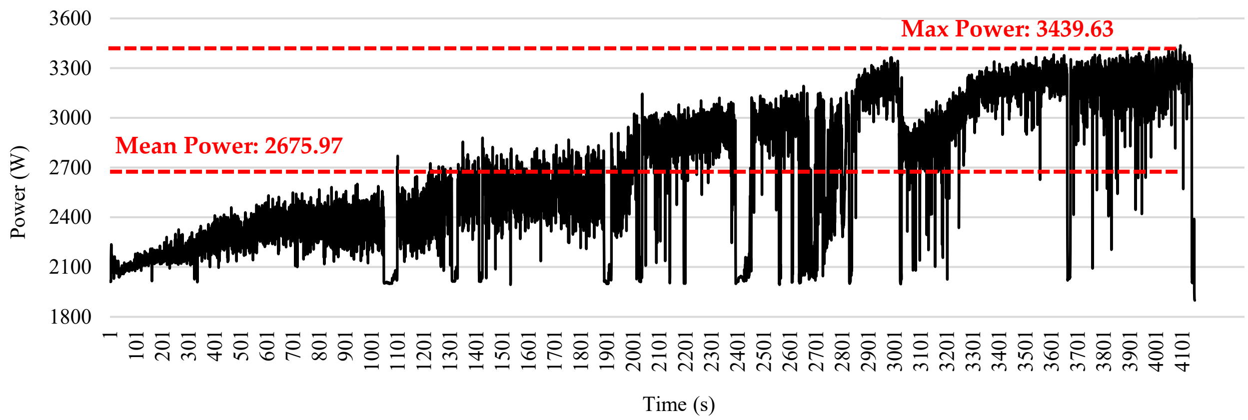


Figure 5. Test 1—Low Tool Wear at 80 amps.

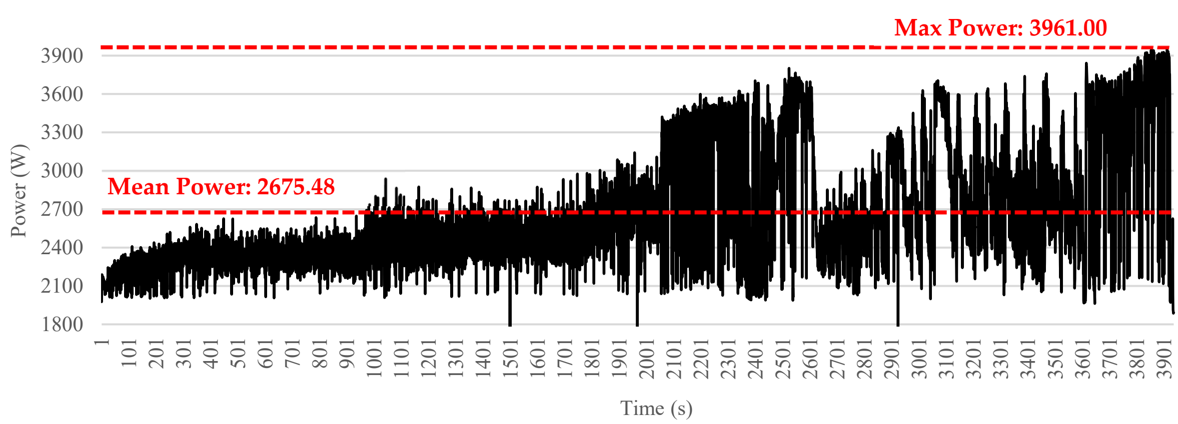


Figure 6. Test 2—High MRR at 100 amps.

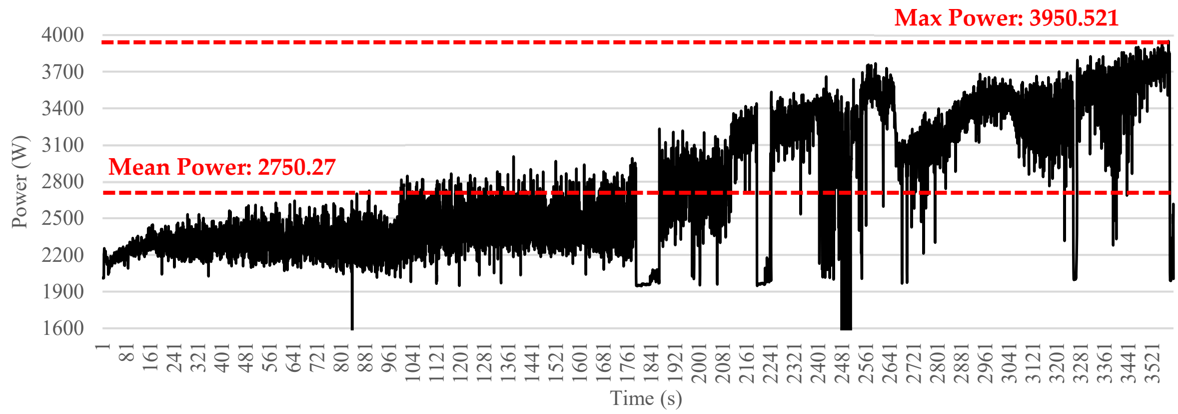


Figure 7. Test 3—Low tool Wear at 100 amps.

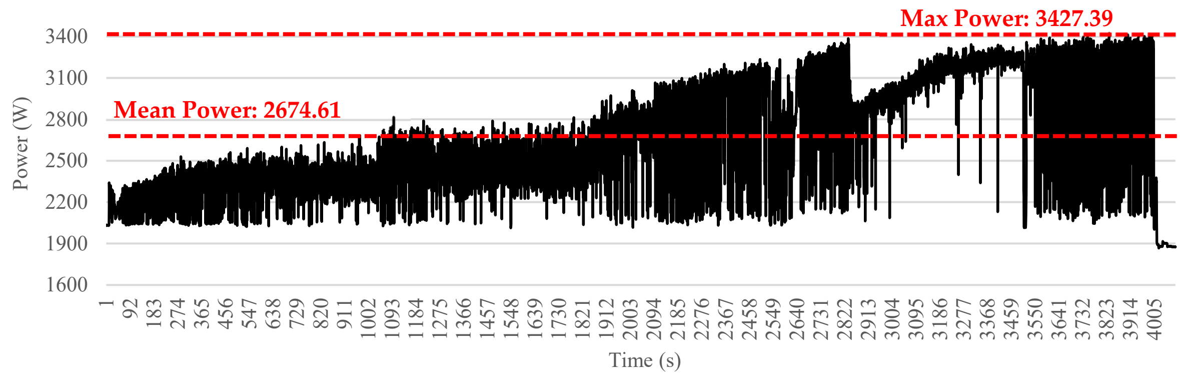


Figure 8. Test 4—High MRR at 80 amps.

Upon analyzing the results seen in Table 3, it became evident that Test 3, which used the preset "Low Tool Wear, 100 A", was the most energy-efficient and time-effective setting among all the tests. This test achieved the shortest machining time of approximately 3716 s and consumed the least amount of total energy, 10,220.4 kJ. Furthermore, this preset recorded the highest spark current value of 28.91 A, indicating a more aggressive electrical discharge rate. Despite the higher current, the overall system efficiency was enhanced, as indicated by the lowest energy-per-second ratio among all the tests. This suggests that a higher pulse current, when optimized correctly, can result in faster machining without significantly increasing energy costs.

In contrast, Test 1, corresponding to the "Low Tool Wear, 80 A" preset, was the least efficient of the four. It had the longest machining time of approximately 4303 s and consumed the highest total energy, 11,523.6 kJ. Although the spark current was considerably lower at 18.19 A, the longer operational time offset any potential energy savings, leading to an overall reduced efficiency. Notably, the refrigeration energy consumption in this case was also the highest, indicating longer support system usage owing to the extended machining duration.

Tests 2 and 4, which used the "High MRR" presets at 100 A and 80 A, respectively, showed similar performance. Their machining times and total energy consumption figures were slightly higher than those of Test 3 but lower than those of Test 1. Their energy efficiency (measured in joules per second of machining time) remained relatively constant at approximately 2676.24–2673.36 J/s, further highlighting that small differences in machining duration can significantly affect overall energy usage. This can also be seen in a detailed analysis of the last 100 s of the manufacturing cycle, when the power graph is normalized and overlapped with other types of presets, as reported in Figure 9.

Table 3. Test case results.

	Parameters	Total Time	Base Energy kJ	Machining Energy kJ	Total Energy kJ	External Aux System (Refriger-ation) kJ	Fixed Spark Current A	Energy per Second J/s	Verdict
1	Low Tool Wear 80 A	01:11:43.314	6886.8	4636.8	11,523.6	12,909.9	18.19	2677.68	Worse Parameter
2	High MRR 100 A	01:07:48.747	6508.8	4377.6	10,890	12,206.2	17.78	2676.24	Neutral
3	Low tool Wear 100 A	01:01:56.287	5943.6	4284	10,220.4	11,148.8	28.91	2750.04	Best Parameter
4	High MRR 80 A	01:10:26.957	6764.4	4539.6	11,300.4	12,680.8	15.76	2673.36	Neutral

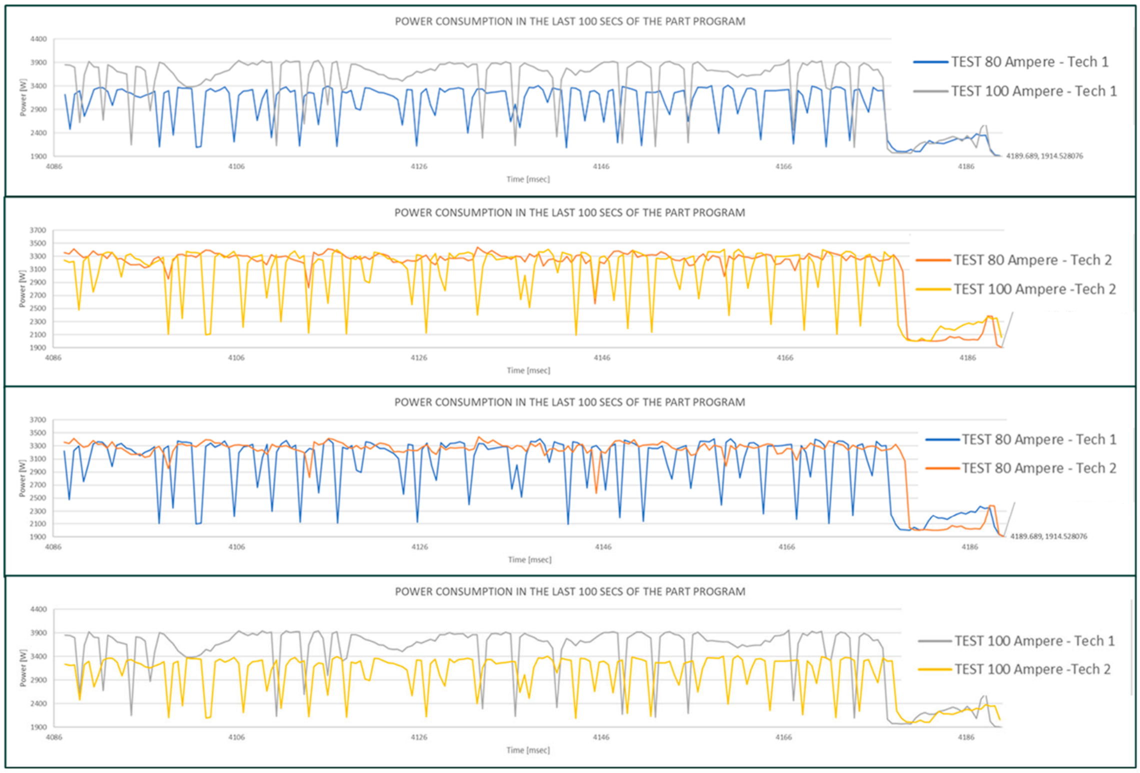


Figure 9. Power consumption of the four tests.

The energy consumed by the refrigeration unit in all the tests was substantial, accounting for more than the energy used in actual machining. However, Test 3 again stood out, with the lowest refrigeration energy demand (11,148.8 kJ), likely due to the reduced overall operation time. This reinforces the importance of minimizing machining duration, not only for power savings at the electrode but also to reduce the energy draw from auxiliary systems, which could constitute a significant share of the energy consumed.

In conclusion, this study demonstrates that the preset of Test 3 (Low Tool Wear, 100 A) offers the best compromise between machining speed and energy efficiency. It outperformed the other presets in every metric considered—shortest machining time, lowest total energy, and highest energy efficiency—making it the optimal choice for applications in which tool wear is manageable. However, Test 1 (Low Tool Wear, 80 A) is less favorable because of its longer machining time and higher total energy cost, despite its conservative current setting.

3.2. Standardized Electrode Shape Experiment

The results obtained from the initial experiment indicate the optimal solution for the impeller case study; however, the complex geometry of the electrode introduced significant challenges concerning the repeatability and reproducibility of this solution. The variability in electrode wear patterns, alterations in flushing fluid dynamics, and unpredictability of debris formation collectively influenced the total energy consumption and degradation characteristics of the electrode over the duration of machining. To address these uncertainties, a second experiment was conducted using a simplified electrode geometry. Specifically, a standardized graphite electrode was fabricated as a rectangular cuboid measuring 90 mm × 90 mm × 20 mm (length × breadth × height), as presented in Figure 10.

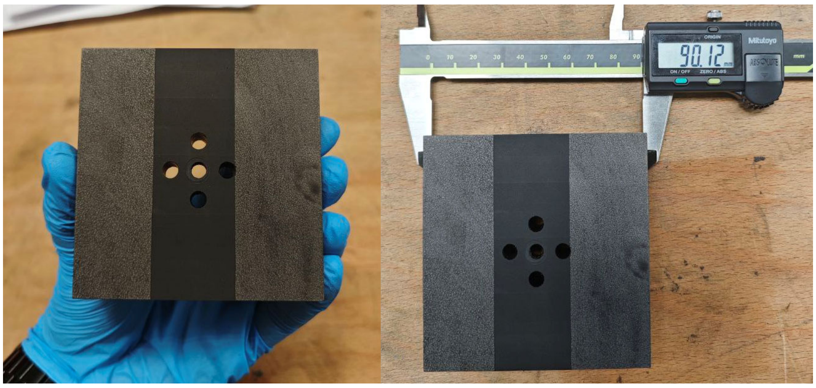


Figure 10. Standard electrode geometry used for tests.

A comprehensive set of 18 trials was performed, systematically varying the EDM parameters, including the discharge current, pulse duration, and other inherent machine "technology" settings or presets. Specifically, in this experiment, another preset was used in addition to presets 1 and 2 used in previous experiments. All three presets and their specifications are given in Tables 4 and 5. Each experimental run involved the erosion of a consistent metal volume of 5400 mm^3, defined by the intended contact area dimensions of 90 mm × 30 mm × 2 mm, as shown in Figure 11.

Table 4. EDM machine presets (technologies).

Tech 1 High MRR			**Tech 2 Low Tool Wear**			**Tech 3 50% & 50%**		
Pulse Time (T)	154	µs	Pulse Time (T)	422	µs	Pulse Time (T)	237	µs
Pulse Gap (P)	87	µs	Pulse Gap (P)	87	µs	Pulse Gap (P)	87	µs
Current	User-Defined	A	Current	User-Defined	A	Current	User-Defined	A
Voltage	100	V	Voltage	100	V	Voltage	100	V

Table 5. User-defined parameters for the experiment.

18 Tests Removing 5400 mm^3 (90 mm × 30 mm × 2 mm)	
40	1 (High M.R.R.)
60	2 (Low Tool Wear)
80	3 (50% & 50%)
100	
120	
140	

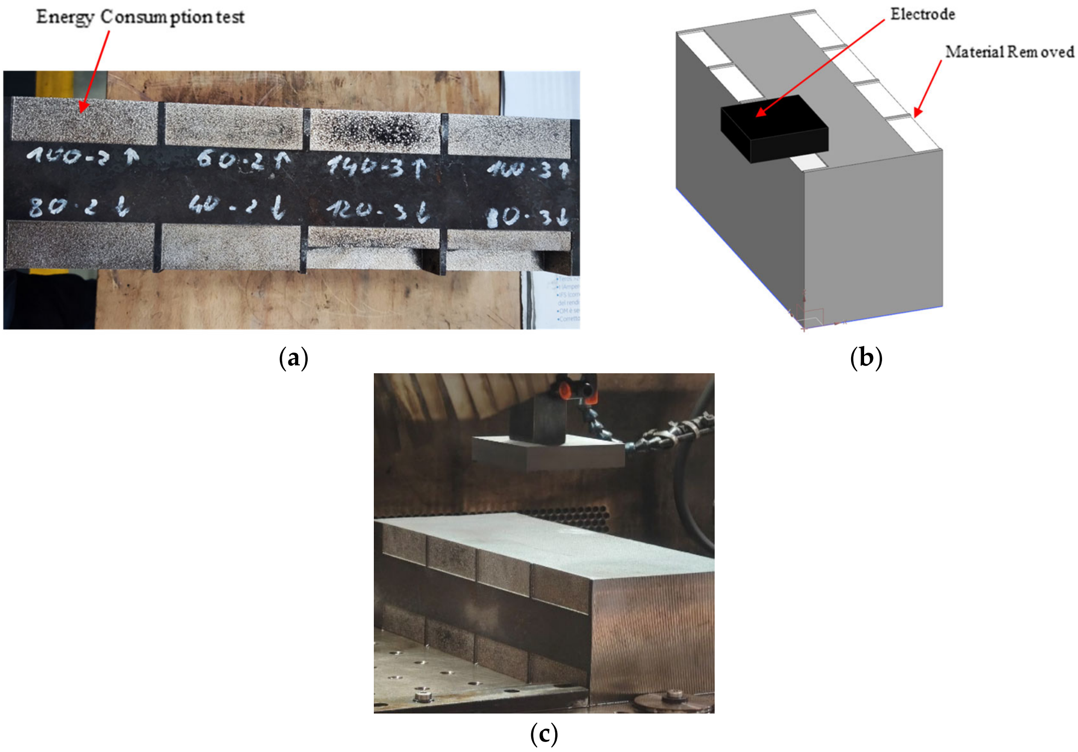


Figure 11. (**a**) Billet showing electrode indents after machining, (**b**) schematic of electrode with respect to raw material, and (**c**) raw material setup on EDM machine.

During these tests, the power sensors recorded the electrical load of the EDM machine, enabling the calculation of total energy consumed for each 5400 mm^3 removed. From this, the SEC for material removal was computed as a key metric for sustainability. In parallel, the graphite tool was closely examined for evaluating electrode wear after each test by measuring the electrode before and after machining.

From the initial 18 trials, trends have been highlighted. The results are reported in Table 6 in the Test ID column, and the test cases are named by the current value and type of preset used. For example, for TEST 140-3, the current used was 140 amperes, and the preset used was Tech 3. The data showed that aggressive EDM parameters that increased the material removal rate (MRR) dramatically shortened the machining time for a given volume. In contrast, more conservative settings (designed to minimize tool wear) led to much longer erosion times. The faster the removal, the lower the total energy consumed in completing the cut, even if the instantaneous power draw was higher. In fact, it was found that "higher machining time" and, hence, slower cutting, led to higher overall energy consumption, whereas a higher MRR resulted in lower specific energy consumption. This outcome was consistent across the trials and was a crucial insight, indicating that any strategy to reduce machining time (within practical limits) would directly save energy per part. The observed reduction in machining time with increasing discharge current, without a proportional increase in total energy consumption, can be attributed to the decreasing relative contribution of auxiliary system overheads. At lower currents, prolonged erosion times result in the extended operation of subsystems, such as dielectric circulation, machine control units, and servo motors. These auxiliary components contribute significantly to the total energy footprint during long cycles. In contrast, higher currents remove material more aggressively, thereby shortening the overall operation duration and effectively compressing the auxiliary energy load into a smaller time frame. This shift leads to lower specific energy consumption (SEC) values at higher-current settings, despite the rise in instantaneous power.

Table 6. Results for SEC tests on a simple geometry.

	Total Erosion Time	Delta	Energy Consumption	Delta	Average Energy Consumption Every Second	Delta	Removed Material	Material Removal Rate	Specific Energy Consumption
TEST ID	**[min]**	**[%]**	**[kWh]**	**[%]**	**[Wh]**	**[%]**	**[mm^3]**	**[mm^3/min]**	**[Wh/mm^3]**
TEST 140-3	15.3	−88%	0.82	−81%	1.10	0%	5184	338.087	0.159
TEST 120-3	17.8	−86%	0.89	−80%	0.98	−10%	5688	319.285	0.156
TEST 140-2	19.1	−85%	1.00	−77%	1.12	2%	5400	283.394	0.186
TEST 140-1	22.0	−82%	1.02	−77%	0.88	−20%	5400	245.440	0.190
TEST 100-3	23.6	−81%	1.10	−75%	0.87	−20%	5184	219.542	0.213
TEST 100-2	24.1	−81%	1.11	−75%	0.98	−11%	5184	215.094	0.214
TEST 120-1	27.1	−78%	1.17	−73%	0.82	−25%	5400	199.015	0.217
TEST 120-2	24.2	−81%	1.18	−73%	1.03	−6%	5400	222.848	0.219
TEST 80-3	29.4	−77%	1.27	−71%	0.82	−25%	5688	193.518	0.224
TEST 80-2	30.3	−76%	1.30	−70%	0.92	−16%	5688	187.734	0.229
TEST 100-1	32.0	−75%	1.31	−70%	0.80	−27%	5400	168.763	0.243
TEST 80-1	44.0	−65%	1.75	−60%	0.77	−30%	5400	122.625	0.323
TEST 60-3	52.7	−58%	2.11	−52%	0.82	−25%	5382	102.190	0.391
TEST 60-1	73.5	−42%	2.69	−38%	0.78	−29%	5400	73.517	0.498
TEST 40-2	75.0	−40%	2.74	−37%	0.80	−27%	5688	75.849	0.482
TEST 40-1	125.6	0%	4.37	0%	0.74	−32%	5400	42.992	0.810

The SEC showed a distinct inverse correlation with the machining current. At higher currents (e.g., 140 A), the SEC dramatically decreased to approximately 0.19 Wh/mm^3 due to the significantly reduced erosion time and thus lower auxiliary system energy usage. Conversely, at lower currents (e.g., 40 A), the SEC increased to around 0.81 Wh/mm^3, reflecting extended machining durations that disproportionately amplified energy overheads. Test 140-3, characterized by high-current and balanced technology settings, was the most energy-efficient scenario, with a SEC of just 0.159 Wh/mm^3, whereas Test 40-1 showed the highest SEC of 0.810 Wh/mm^3. This nearly fivefold difference clearly emphasizes the importance of parameter optimization to minimize total energy consumption and increase sustainability. The observed SEC trends offer manufacturers practical guidance—strategically increasing discharge currents, within electrode wear limits, can markedly improve sustainability and reduce operational costs, particularly by cutting the auxiliary system energy demands associated with prolonged machining cycles.

An electrode wear analysis was also performed using the two extreme test cases from experiment 2 in Table 6 (Tech 3 was ignored, as in most cases, the results were not optimal). A comparison was made between Test 1 (higher current of 140 amperes, Technology 1) and Test 2 (much lower current of 40 amperes, Technology 2). As reported in Figure 12, both tests aimed to remove an identical volume of approximately 129,600 mm^3 from the workpiece. However, notable differences emerged between the two tests regarding erosion time, achieved volume removal, and electrode tool wear.

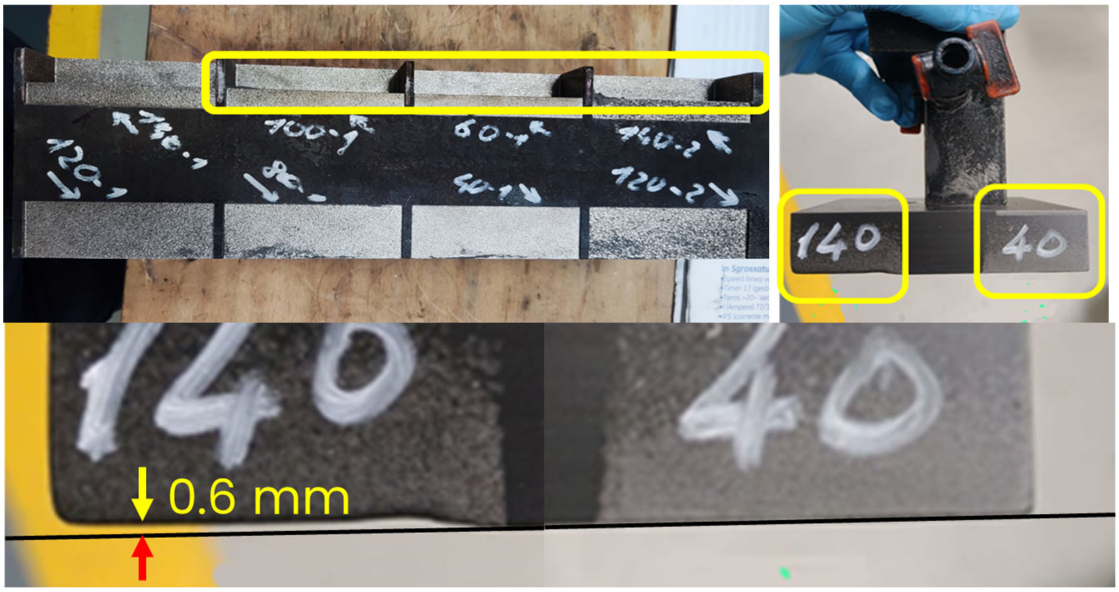


Figure 12. Comparison of TEST 140-1 and TEST 40-2.

Test 1 (140 A) was conducted aggressively, prioritizing high material removal rates, and the machining was completed in approximately 210 min. However, the actual volume removed was marginally below the intended target, specifically 127,980 mm^3, reflecting a shortfall of approximately -1.25%. The close-up images provided clearly show the measurable electrode wear—approximately 0.6 mm of material loss on the graphite electrode, as seen in Figure 12. Owing to this wear, the electrode's ability to achieve the full intended machining depth was slightly compromised. Therefore, a time adjustment was calculated to account for the shortfall, adding an additional 2.6 min (1.25%) of machining time for a corrected total duration of 212.6 min had the full volume been achieved.

Test 2, which employed a more conservative approach at 40 A (Technology 2), demonstrated a drastically different scenario. This low-current method significantly minimized electrode wear so effectively that the removed volume matched precisely the expected 129,600 mm^3 without any measurable deviation. However, this advantage came with an exceedingly prolonged erosion time of 2010 min (over 33 h), highlighting the practical trade-off between electrode longevity and productivity.

In terms of electrode degradation, a clear increase in volumetric wear was observed with increasing current. However, when normalized over machining time, the wear rate (expressed in mm^3/min) showed only a modest increase. For instance, at 40 A, the wear rate was approximately 0.018 mm^3/min, while at 140 A, it rose to 0.023 mm^3/min. This relatively low increase in wear rate compared to the large decrease in machining time suggests that higher-current presets provide a favorable trade-off, especially when the electrode replacement cost is not a limiting factor. This also reinforces the viability of high-current EDM as a productivity-oriented yet sustainable choice.

4. Conclusions

This research rigorously investigated the correlation between energy consumption and electrode wear in die-sinking Electrical Discharge Machining (EDM), addressing a notable gap in the current literature concerning comprehensive empirical evaluations of real-time energy usage integrated with precise electrode wear assessments. EDM has long been recognized as a crucial process for machining intricate geometries in challenging materials. However, prior studies have typically focused either solely on theoretical energy modeling or isolated analyses of individual machining parameters. These studies often neglected a holistic examination of the combined influences of process settings, auxiliary system loads, and electrode deterioration.

The novelty of the present study lies in its methodical integration of empirical data collection techniques and robust analytical methodologies, facilitating a holistic appraisal of EDM operational dynamics. Thus, this study explicitly considered auxiliary energy demands, particularly from refrigeration systems. By doing so, it provided a comprehensive portrayal of the energy profile during EDM operations. This is a distinct advancement beyond the conventional fragmented analytical approaches prevalent in the existing literature.

The experimental outcomes yielded significant insights. They particularly highlighted that optimized high-current EDM parameters substantially improved both machining productivity and energy efficiency. This counters the prevalent notion that aggressive discharge settings invariably lead to undesirable electrode wear. Specifically, comparative analyses between high-current (140 A) aggressive machining and conservative low-current (40 A) settings highlighted a critical trade-off. The conservative parameters successfully minimized electrode wear to negligible amounts but at the cost of drastically increased machining times and correspondingly higher cumulative energy consumption. In contrast, the strategically optimized high-current setting notably reduced the overall machining time by up to an order of magnitude while maintaining acceptable electrode wear levels. Quantitative metrics reinforced this finding, demonstrating a lower specific energy consumption (SEC), a pivotal sustainability indicator, under high-current, optimized conditions.

These results have substantial implications for advanced manufacturing sectors, particularly the aerospace, automotive, and precision tooling industries, where operational efficiency, cost-effectiveness, and sustainability are paramount. This study empirically substantiates the viability and benefits of employing aggressive EDM settings. For example, for operations where electrode wear within ~0.6 mm is acceptable, using a 140 A discharge current with the High MRR preset is strongly advised, as it significantly reduces machining time and achieves the lowest specific energy consumption (0.159 Wh/mm^3) among the tested settings. On the other hand, for applications requiring minimal tool wear, the Low Tool Wear preset at 100 A offers a balanced compromise between machining speed and electrode longevity. Future studies can explore intermediate current levels (e.g., 60 A, 120 A) to identify more precise thresholds for optimization. Additionally, investigating alternative electrode materials such as copper–tungsten or composite electrodes may reveal further opportunities for enhancing wear resistance while maintaining energy efficiency. Expanding the analysis to include different workpiece materials and dielectric fluids could also help generalize these findings across a broader range of EDM applications.

For now, this study provides practical guidelines to enable process engineers to significantly enhance productivity and energy efficiency without incurring prohibitive electrode wear or environmental penalties.

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Abbreviations

The following abbreviations are used in this manuscript:

EDM	Electrical Discharge Machining
SEC	Specific Energy Consumption
MRR	Material Removal Rate
MCE	Manufacturing Cycle Efficiency
AE	Acoustic Emission
PLC	Programmable Logic Controller
VHP	Very High Performance (as in FORM 3000 VHP)
RS485	Recommended Standard 485 (a serial communication protocol)

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