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Optimum Material Removal in Electrical Discharge Machining through Advanced Control Integration of PSoC Microcontroller

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ABSTRACT

Electrical Discharge Machining (EDM) is an advanced non-traditional method for precision material removal using repeated electrical discharges. It utilizes a programmable tool electrode to intricately shape designs. Existing research has highlighted that current EDM control systems are often intricate, sluggish, and costly. In addressing these limitations, there is a notable opportunity to enhance the design of an advanced EDM control system, that is both sophisticated and cost-effective. Therefore, the authors proposed an integration of a pulse generator, control system, timer, and flushing system using a Programmable System-on-Chip (PSoC) microcontroller to regulate the gap between an electrode a workpiece, flushing system, and the overall EDM machining process. The pulse generator algorithm was developed to efficiently manage T_{on} *and* T_{off}*, while the Proportional Integral Derivative (PID) algorithm was employed to uphold the gap between the electrode and the workpiece. Additionally, the timer algorithm was closely associated with the machining process timing. Activation of the second servo pump at 80% of machining was implemented to enhance the flushing pressure rate. The EDM-PSoC system was utilized with the experiment conduction at three different current settings (2A, 4A, and 6A) over five periods, and results were compared with the EDM-Existing system. The experimental outcomes revealed a notable increase in Material Removal Rate (MRR), averaging 0.1348 mm*^{3}*/min at 6A. Furthermore, the EDM-PSoC system demonstrated high consistency in each repetition experiment conducted at lower currents, achieving MRRs of 0.0142 mm*^{3}*/min at 2A and 0.0560 mm*^{3}*/min at 4A. Comparatively, the EDM-PSoC system improved the average MRR by 49% compared to the traditional EDM-Existing system. The depth of the machined workpiece produced by the EDM-PSoC system was deeper than the EDM-Existing system at equivalent time settings. Consequently, the findings indicate that the EDM-PSoC system achieved a higher MRR relative to the conventional EDM procedure, thus improving significantly the system efficiency.*

Keywords: Electrical Discharge Machining (EDM); Material Removal Rate (MRR); PSoC Microcontroller

INTRODUCTION

Electrical Discharge Machining (EDM) is one of the earliest advanced non-traditional machining processes, also called a non-conventional machining material removal process (Chakraborty 2021; Kalita 2023). It applies a non-contact thermoelectric mechanism between a workpiece and an electrode (Naskar 2022). Electrical Discharge Machining is also well-established for making high precision and complex-shaped parts based on thermal erosion concept, on any electrically conductive material such as hardened steels, carbides, and ceramics (Karpuschewski 2021; Niamat 2017).

EDM plays a pivotal role in modern manufacturing due to its ability to precisely machine complex shapes and geometries in electrically conductive materials, regardless of their hardness (Qudeiri 2020). Unlike traditional machining methods that can struggle with hard materials and intricate designs, EDM excels by using electrical discharges to erode the material (Simao). This process does not apply mechanical force to the workpiece, which eliminates the risk of deformation and stress (Xuyang), ensuring high precision and maintaining the integrity of the material. Additionally, EDM is capable of producing superior surface finishes and handling hardened materials without the need for pre-machining or post-process heat treatments (Lin 2012). This makes EDM a versatile and efficient solution for manufacturing components that demand high accuracy and fine details.

The applications of EDM span across various high-precision industries, showcasing its versatility and importance. In injection molding, EDM is utilized to create detailed molds and dies that require complex shapes and fine surface finishes (Maradia, 2018). This precision extends to small hole drilling, where EDM can produce tiny, accurate holes in challenging positions, such as inclined faces. In die casting, EDM enables the creation of highly tailored dies with sharp internal corners, deep ribs, and intricate features, which are difficult to achieve with conventional methods (K. V. Kumar 2016). The tool and die making industry benefits significantly from EDM's ability to produce precise molds (Roeder, 2019), dies (Shastri 2022), and stamps, essential for aerospace, automotive, and medical device manufacturing (Jain, 2021).

Furthermore, EDM is crucial in the production of intricate medical devices and surgical tools, where high precision and accuracy are paramount (Prakash 2022). In the aerospace sector, EDM is used to machine complex components like turbine blades and engine parts, which require intricate shapes and fine details. The electronics industry relies on EDM to manufacture semiconductor parts and connectors with high precision. EDM's capability to prototype and create experimental parts with complex geometries makes it invaluable in research and development. Additionally, the telecommunications industry uses EDM to fabricate precise connectors and infrastructure components, while the manufacturing machinery sector employs EDM to create complex parts such as gears and threads. Overall, EDM's unique advantages and wide range of applications underscore its significance in modern manufacturing processes, where precision and complexity are crucial.

Material removal rate (MRR) is an important performance parameter in the EDM system. It refers to the ratio of weight difference for the workpiece, before and after the machining process, to the density of workpiece material and machining time (Çakıroğlu 2020; Fadhil 2022; Perumal 2021). Moreover, MRR enables the quantifying of machining speed (S. Kumar et al. 2020). Previous researchers have reported numerous studies on EDM design techniques, intended to enhance and improve the performance measures of machining process using several types of microcontrollers. In 2012, Zhang et al. (2012) developed a new technique to improve servo control system stability using type-2 fuzzy logic. In their study, type 1 fuzzy control was used to detect discharge state, while type 2 fuzzy was used to control the output of servo-fed speed.

Besides, Andromeda (T. Andromeda 2015) emphasized on Particle Swarm Optimization (PSO) technique, which has been implemented in Proportional Integral Derivative (PID) controllers to monitor the position of electrode towards a workpiece. The improvement of MRR is continuously performed by controlling the constant of ignition time delay. Similar researcher, Andromeda et al. (T. Andromeda et al. 2013) reported on the capabilities and effectiveness of Differential Evolution (DE) algorithm in PID controller to monitor the electrode gap. The experimental results showed that the DE was better than the PSO technique based on Integral Absolute Error (IAE) with minimum fitness function to reach cumulative setting parameters. Next, a flexible machine controller has been proposed to improve MRR, tool wear rate (TWR), and surface roughness (SR). Supervisory Control and Data Acquisition (SCADA) were also linked with Programmable Logic Controllers (PLCs) to optimize the parameters of EDM process for rough, semi-finish, and finishing (Perumal 2021). Furthermore, a spark gap controller has been developed for a tabletop micro EDM setup using AT89C51 microcontroller (Abdullah 2020). The research focused on the effect of DC voltage supply, the value of capacitance, and spark gap on MRR values. Increasing the value of DC voltage has decreased the capacitance and spark gap, led to greater MRR values. Moreover, Thampi, Sureshkumar, and Luka (Thampi 2018) have proposed a low-cost automatic spark gap adjustment system using Arduino UNO R3 for micro EDM tabletop size. Another work by Tseng et al. (Tseng 2018) exposes the design of automated EDM system with real-time monitoring that applied the Ziegler-Nichols method with PID onto nano iron colloids. The real-time parameter data were displayed on VisSim software to diagnose arisen problems during the machining process.

Due to the digital revolution in industries, it requires embedded systems to reduce performance. In this research, a programmable system on chip (PSoC) microcontroller has been chosen to be implemented in EDM design system. The PSoC consists of central processing unit (CPU) core, configurable analogue, and digital blocks with a combination of several chips for mutual performance function. A single PSoC device manages to integrate almost 100 digital and analogue peripheral functions. It has low power consumption, able to minimize board space, and capable to reduce design time and cost, thus improving the system efficiency (Chen 2010; Zhou 2019). This device possesses several other advantages such as flexibility, integrated, and programmable analogue. The PSoC microcontroller has the performance of 24 MHz and 4 MIPS (million instructions per second), which contributes to high-speed processing data, especially to control the voltage gap for EDM system. Due to these beneficial specifications and characteristics, PSoC microcontroller has been selected as the central system in the newly developed EDM system. A control system is an essential component in EDM, which controls the gap between an electrode and a workpiece (Qudeiri 2020). Precise gap control through the adoption of PSoC microcontroller can improve MRR values (Singh 2022). From the literature studies on the measurement of EDM performance, there is a crucial need to integrate the control system with other parameters to improve the machining performance.

The primary concern lies on the development of high-speed processing, and stable as well as efficient control system to enhance EDM performances. In response to this issue, the implementation of PSoC has been chosen as the strategic approach. The efficacy of this methodology has been assessed through a comparative analysis of MRR against the backdrop of existing EDM systems. Previous research indicates that various enhancements can significantly improve EDM performance. However, recent study faces the challenge of concurrently refining multiple functions within a singular system. These functions include the precise control of electrode distance relative to the workpiece, upgrading the pulse generator and flushing system, and establishing the optimal current setting. Overcoming these challenges hold the promise of reducing machining time and augmenting MRR. Existing literature underscores the complexity, sluggish speeds, and high costs associated with most control systems. This limitation can be mitigated through the implementation of sophisticated EDM control system design. Therefore, the study aimed to investigate the comparative performance of EDM-PSoC and EDM-Existing systems across various current settings. The study delved into ignition time delays, spark discharge conditions, and MRR, to provide a comprehensive understanding of the systems' efficacy under different machining conditions. Forwardly, the efficient system highlighted the performance of EDM-PSoC system in managing ignition time delays, particularly for longer durations, across 2 A, 4 A, and 6 A current settings. Moreover, the MRR analysis aimed to emphasize the effectiveness in delivering stable machining conditions and consistently efficient material removal processes across a range of current settings.

METHODOLOGY

Initially, EDM was divided into two separate parts, namely the EDM structure mechanism and the controller box, as illustrated in Figure 1. The EDM structure mechanism consisted of two parts: the mechanical part and the electrical part (Gouda 2021). The mechanical parts included the existing EDM structure, ball screw, tool holder, linear guide, dielectric tank, mini jaw clamp, filter, electrode, and workpiece. Many of these mechanical parts were reused from the existing set and were only improved based on the new design. Meanwhile, the electrical part included the DC servo motor, flushing system, and dielectric medium. Another component of EDM was the controller box, which contained a power supply unit, PSoC microcontroller, user interface device, input-output interface (IO) board, and resistor bank.

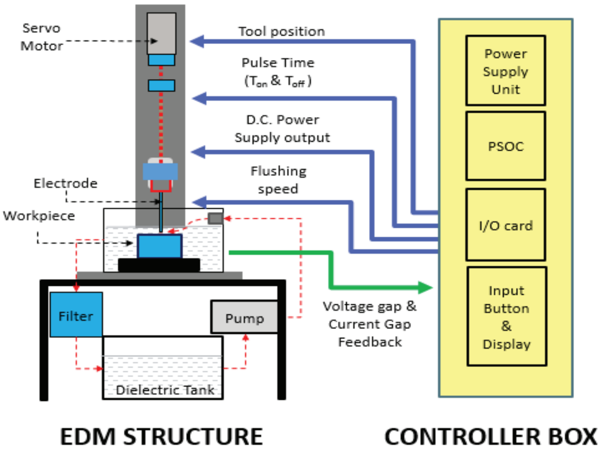

FIGURE 1. EDM Block Diagram

SOFTWARE DEVELOPMENT

The system process began by inputting data into parameter settings (time, pulse for Ton and Toff, and voltage gap) through buttons, with the information displayed on liquid crystal display (LCD). Subsequently, the start button was pressed, initiating the execution of the main program within a continuous loop. The main program encompassed four key activities: counting the machining time, controlling the servo motor position, generating pulses, and regulating the flushing speed. The program was concluded, once all specified activities had been successfully carried out.

TIME MACHINE

Timers stand out as one of the most frequently employed peripherals in embedded designs, serving the purpose of measuring the duration of operation or establishing time limits for specific processes. In the re-designed EDM system, a timer was implemented to regulate the operation/machining process duration, guided by the preset time input during the initial stage. The timer functioned in seconds and minutes where the ongoing operation time was prominently displayed on the LCD screen. Once the timer reached the pre-set time, it ceased counting, bringing the operation to a halt, accordingly.

SERVO MOTOR POSITION CONTROL

The elevated analog voltage signal originating from the primary circuit of the EDM underwent conversion to a lower analog voltage with the aid of voltage feedback board. Subsequently, the analog voltage signal from the voltage feedback board underwent further transformation into a digital signal through the analogue to digital converter (ADC) within the PSoC microcontroller hardware. Employing the PID algorithm, the calculation of direction and velocity speed of the servo motor rotation took place. The resulting PWM signals for motor direction and velocity speed were then transmitted through a high-power motor module. The flowchart in Figure 2 illustrates the servo motor program.

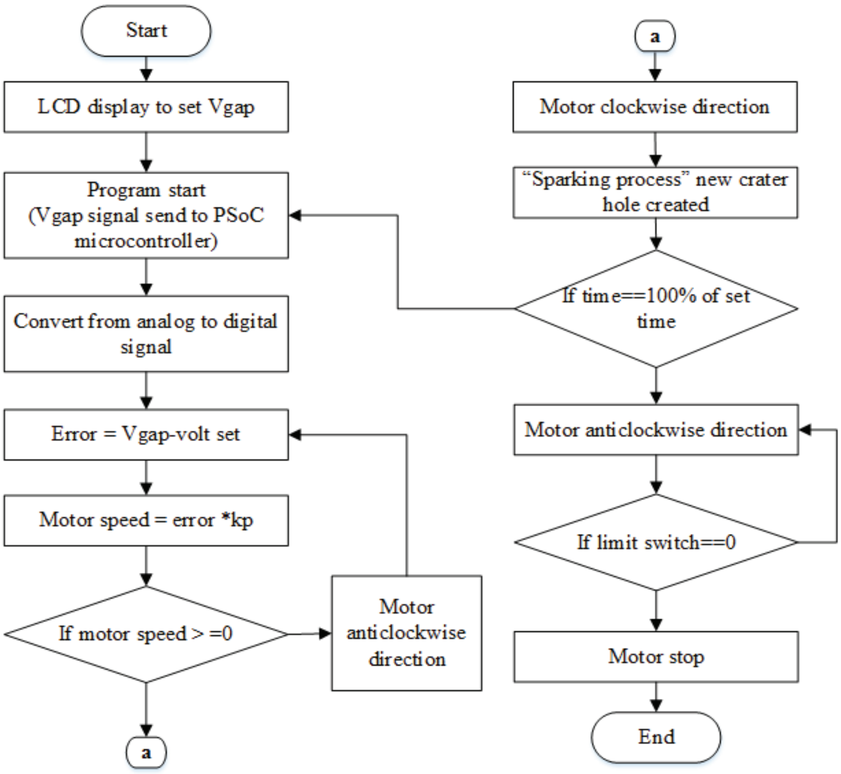

FIGURE 2. Servo Motor Program

PULSE GENERATOR AND FLUSHING SYSTEM

In this study, the pulse generator signal was programmed directly into the PSoC microcontroller, a departure from the use of 555 timers in the previous design. The parameters Ton and Toff were configured during the initial stages before initiating the main program. The PWM signal generation ceased once the elapsed time reached 100% of the preset machining time. Additionally, the Jet flush-method was chosen for the EDM-PSoC system. This method involved expelling dielectric fluid through a nozzle, directed towards the machining area. The jet pressure induced a flow in the discharge gap, effectively carrying away debris from the gap. Prior to the machining process, servo pump#1 was initiated to flush the workpieces and fill the dielectric tank. When the machining time reached 80% of the predetermined time, servo pump#2 was activated. Both servo pump#1 and pump#2 were subsequently halted when the machining time reached 100% of the set machining time.

EXPERIMENTAL SETUP

The EDM setup comprised of power supply, spark generator or pulse generator, servo system, mechanical structure, and dielectric fluid, as illustrated in Figure 3. Machining tests were conducted by utilizing two distinct systems: the new EDM system, also known as the EDM-PSoC system, and the existing EDM system, denoted as EDM-Existing system. Throughout the experiment, two parameters were maintained constant: (a) temperature of the dielectric fluid, and (b) current consumption during the machining process.

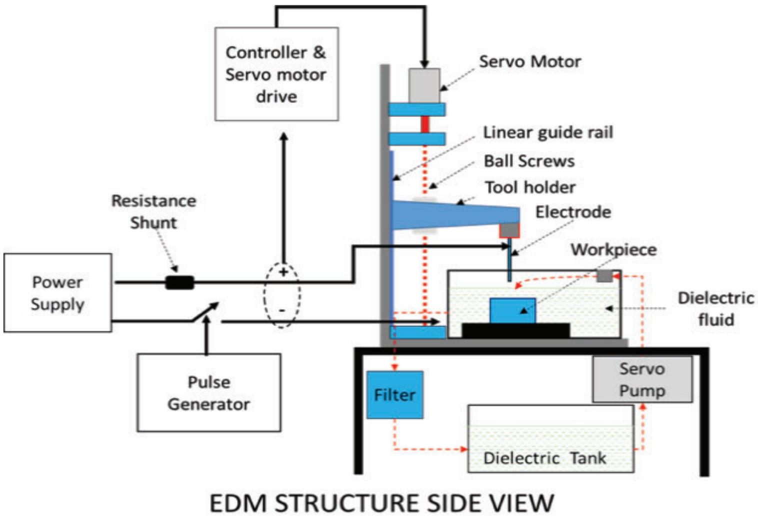

FIGURE 3. Overall EDM system

Figure 4 depicts the schematic diagram of experimental setup, designed to measure the voltage gap (Vgap) and the current gap (Igap) during the machining process. To capture the signal, both the reference (grounding lead) of probe 1 and probe 2 were connected between the resistor and the electrode. The probe 1 (Ch 1) of Oscilloscope#2 was linked to the workpiece to measure the Vgap. It is essential to note that the Ch 1 was inverted; otherwise, the signal would be displayed in a reverse mode. Conversely, the probe 2 (Ch 2) was connected to the positive direct current (DC) power supply for measuring the voltage gap. The determination of current gap was achieved using Kirchhoff's Law formula, as expressed in Equation (1).

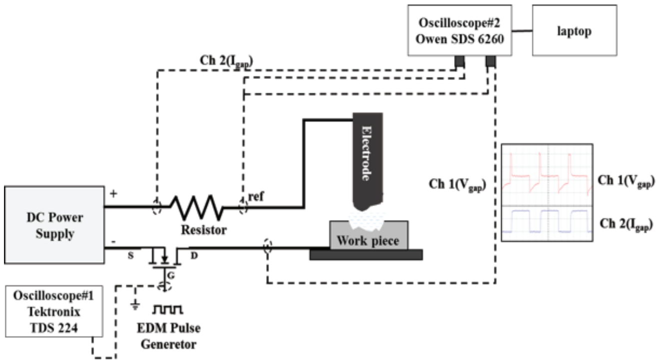

FIGURE 4. Setup to measure voltage and current gap

$$I_{gap} = \frac{V_{p-p}}{R_{total}} \qquad (1)$$

Experiments were carried out using two different workpieces for the EDM-PSoC system and the EDM-Existing system, respectively. Material of the workpiece was set to mild steel with a density, r = 7.85 g/cm3 and a dimension of (30×10×10) mm^3. Tungsten is one of the best metallic characteristics to be used as an electrode due to its very high strength, density, hardness, and melting point near to 3420°C (Zhou 2019). Moreover, tungsten is also capable to resist damaging effects of the EDM process very well. In this study, pure tungsten (99.9% of purity) in a cylindrical form with a diameter of 1 mm has been selected as the electrode while a flat-ground rectangular plate of mild steel was selected as the workpiece sample. Vitalube EDM oil 99 SD was utilized as the dielectric medium in this study.

Before commencing the experiment, the weight of the workpiece was recorded using an electronic balance (ATX224, Shimadzu, Japan). Subsequently, the workpiece was positioned on an adjustable mini jaw bench clamp, submerged in a dielectric medium. Fifteen individual experimental runs were conducted for both the EDM-PSoC system and the EDM-Existing system, employing current settings of 2 A, 4 A, and 6 A, respectively. The machining process duration varied across five different periods: 10 min, 20 min, 30 min, 40 min, and 50 min. Each experimental run was repeated three times for every time period and current setting in both systems to calculate the average MRR.

Following the completion of the machining process, the servo motor automatically ascended until it reached the limit switch, allowing for detachment of the workpiece from the mini clamping jaw. The workpiece was then dried using an air dryer to eliminate the dielectric medium for precise results. Subsequently, the workpiece was weighed again to determine the weight after the machining process.

Before reusing the electrode in subsequent experiments, the tungsten electrode underwent polishing on emery paper with grit sizes ranging from 400 to 2000. The experiments were conducted at various times and current settings, resulting in a total of 90 recorded runs, in accordance with the design of the experiment table.

MATERIAL REMOVAL RATE

Material Removal Rate is a crucial performance parameter in this research, defined as the erosion rate at which material is removed from the workpiece during the machining period, in minutes. The Shimadzu ATX224 electronic balance, with an accuracy of 0.1 mg and the capability to measure up to 220g, was employed to measure the weight of the workpiece before and after the machining process.

The machining process time (T) for the EDM-PSoC system was pre-determined at the initial setting, while a stopwatch recorded the machining process time (T) for the EDM-Existing system. The MRR was calculated using Equation (2) where Wi and Wf represent the weight of the workpiece, before and after the machining process, r indicates the density of workpiece, and T is the time of EDM machining (measured in minutes).

$$\text{MRR} = \frac{Wi-Wf}{(T)(\rho)} \qquad (2)$$

In this study, an oscilloscope OWON SDS 6260 (SDS 6260, OWON, China) was used to monitor the overall spark discharge conditions, short circuit and actual spark duration/interval in EDM. The spark discharges have been recorded in a computer using OWON oscilloscope software.

RESULTS AND DISCUSSION

TEMPORAL ANALYSIS

The initial investigation into the comparative performance of EDM-PSoC and EDM-Existing systems at varying current settings, namely 2 A, 4 A, and 6 A, unfolds a nuanced picture of ignition time delays. At 2 A, as illustrated in Figure 5a, both the EDM-PSoC and EDM-Existing systems demonstrated minor discrepancies in their average time delays within the lower time delay groups. This suggests a comparable efficiency between the two systems in managing shorter duration delays, indicating a similar performance under these conditions. However, a notable deviation emerged as the time delay extended from the range of 15~19.99 μs to 20~24.99 μs. During this expanded time delay range, the EDM-PSoC system not only exhibited a lower average time delay but also achieved a substantial 39% reduction compared to the EDM-Existing system. This significant disparity indicates that the EDM-PSoC system possesses a more effective discharge process, particularly when confronted with longer ignition time delays. Such findings highlight the potential superiority of the EDM-PSoC system in handling challenging ignition scenarios and underscore its capability to deliver more efficient and precise performance in practical applications.

Advancing to a higher current setting of 4 A, as depicted in Figure 5b, the observed trend persisted, with minor disparities in average time delays for the lower time delay groups between the EDM-PSoC and EDM-Existing systems. However, the notable difference in performance emerged once again as the time delay extended, particularly for higher time delay groups. The EDM-PSoC system consistently outperformed the EDM-Existing system in these instances. The most significant contrast was observed for delays exceeding 25 µs, where the EDM-PSoC system achieved a remarkable 40% reduction in average time delays compared to its counterpart. This finding underscores the enhanced capability of the EDM-PSoC system in managing prolonged ignition time delays, thereby contributing to improved operational efficiency. Such consistent performance superiority of the EDM-PSoC system across varying current settings reinforces its potential as a preferred choice for applications demanding precise and efficient ignition processes, particularly in scenarios involving extended time delays.

Extending the analysis to the 6 A current setting, as illustrated in Figure 5c, a similar pattern emerged, with modest advantages observed for the EDM-PSoC system in the lower time delay groups. However, the distinct superiority of the EDM-PSoC system became increasingly apparent in the higher time delay categories. Notably, the EDM-PSoC system exhibited a noteworthy 21% reduction in average time delays compared to the EDM-Existing system. This consistent performance superiority across different current settings underscores the robustness and effectiveness of the EDM-PSoC system in mitigating ignition time delays, particularly in scenarios involving elevated current demands. The findings suggest that the design and technological innovations incorporated into the EDM-PSoC system contribute to its ability to deliver more efficient and precise ignition processes, even under challenging operating conditions. This consistent superiority highlights the potential of the EDM-PSoC system as a reliable and effective solution for applications requiring rapid and accurate ignition, reaffirming its position as a preferred choice in various industrial settings.

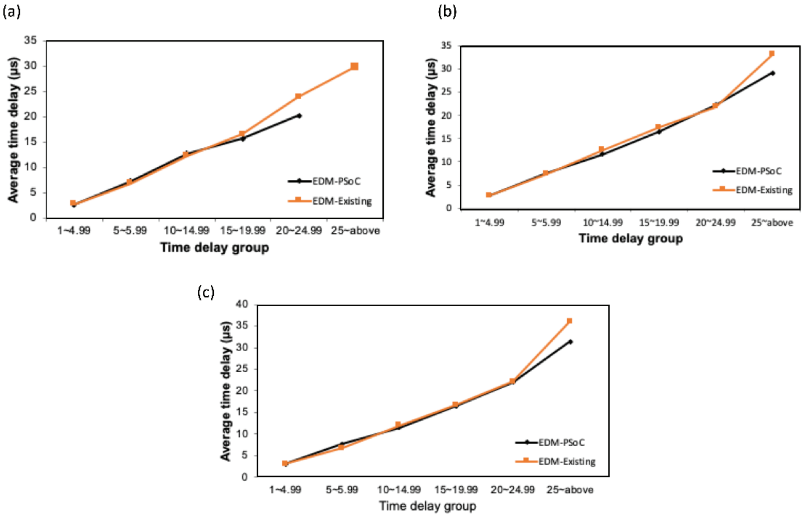

FIGURE 5. Comparison average time delay between EDM-PSoC system and EDM-Existing system for: (a) 2 A, (b) 4 A, and (c) 6 A of current settings

Figure 6 shows three images of holes machined by EDM-PSoC for the current settings of 2 A, 4 A, and 6 A, respectively. The holes were machined for 10 min. As can be seen in the figure, the images found to be darker when the 6 A was applied compared to the 2 A and 4 A.

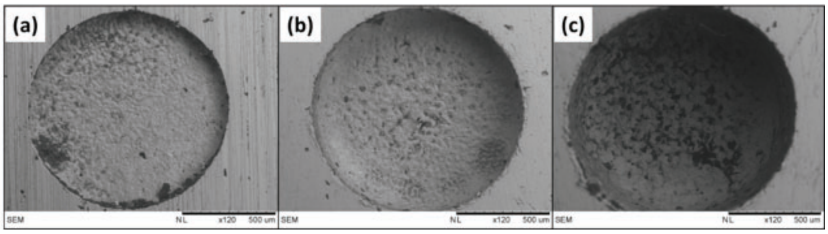

FIGURE 6. Holes depth after machining by EDM-PSoC system at different current settings of (a) 2 A, (b) 4 A, and (c) 6 A, for 10 min machining

The comparison of MRR between the EDM-PSoC and EDM-Existing systems at the 2 A current setting (Figure 7A1a) reveals a clear and distinct superiority of the EDM-PSoC system across various performance metrics. Upon analyzing the MRR values, it becomes evident that the EDM-PSoC system consistently outperforms the EDM-Existing system across the entire range of trials.

Notably, the highest MRR achieved by the EDM-PSoC system, standing at 0.0153 mm³/min, significantly surpasses the highest MRR of 0.0115 mm³/min attained by the EDM-Existing system. This substantial difference highlights the enhanced material removal efficiency of the EDM-PSoC system compared to its counterpart. Moreover, when examining the lowest MRR values, the superiority of the EDM-PSoC system becomes even more pronounced. Even the least efficient trial with the EDM-PSoC system, achieving an MRR of 0.0127 mm³/min, outperforms the lowest MRR of 0.0076 mm³/min recorded with the EDM-Existing system. This stark contrast in MRR values underscores the considerable performance advantage offered by the EDM-PSoC system in terms of material removal efficiency. The superior MRR values achieved by the EDM-PSoC system indicate its enhanced capability to remove material at a faster rate, resulting in higher productivity and efficiency compared to the EDM-Existing system. This finding is particularly significant as it demonstrates the tangible benefits of incorporating advanced technologies, such as PSoC, into EDM systems to improve their performance and productivity.

The observed superiority of the EDM-PSoC system in MRR not only highlights its potential for optimizing machining processes but also emphasizes its relevance in various industrial applications where material removal efficiency is paramount. By providing higher MRR values, the EDM-PSoC system offers a competitive edge in terms of productivity, cost-effectiveness, and overall performance, positioning it as a promising solution for demanding machining operations. Examining the central tendency of MRR the mean MRR ($\bar{x}$) for the EDM-PSoC system stood notably elevated at 0.0142 mm³/min. This indicates a consistently higher average material removal rate compared to the mean MRR of 0.0094 mm³/min achieved by the EDM-Existing system. This implies that, on average, the EDM-PSoC system removed material more efficiently during the machining process at the 2 A current setting (Figure 7A1b). This significant difference in mean MRR values underscores the superior material removal efficiency of the EDM-PSoC system, emphasizing its capability to achieve higher productivity and throughput in machining operations. Furthermore, the standard deviation values provide valuable insights into the consistency of MRR across multiple trials. With a lower standard deviation of 0.0009 for the EDM-PSoC system compared to 0.0012 for the EDM-Existing system, the former exhibits a higher level of consistency in MRR values. This suggests that the EDM-PSoC system not only achieves superior material removal rates but also does so with greater stability and reliability in performance, demonstrating its effectiveness in maintaining consistent machining conditions at the 2 A current setting. The lower standard deviation implies less variability in MRR values across different trials with the EDM-PSoC system, indicating a more reliable and predictable machining process.

Extending the analysis to the 4 A current setting (Figure 9B1a), the superior performance of the EDM-PSoC system remains evident. The highest MRR achieved with the EDM-PSoC, reached 0.0616 mm³/min, significantly exceeds the highest MRR of 0.0460 mm³/min obtained with the EDM-Existing system (Figure 9B1b). Similarly, even the lowest MRR value for the EDM-PSoC, at 0.0497 mm³/min, outperforms the lowest MRR of 0.0312 mm³/min, recorded with the EDM-Existing. The mean MRR for the EDM-PSoC was notably higher at 0.0560 mm³/min compared to the mean MRR of 0.0398 mm³/min for the EDM-Existing. The lower standard deviation of 0.0035 for the EDM-PSoC, in contrast to 0.0038 for the EDM-Existing, indicates higher consistency in MRR values for the former system, affirming its stability and reliability at the 4 A current setting.

At the 6 A current setting, the superiority of the EDM-PSoC system over the EDM-Existing system persists, with precise numerical differences highlighting its performance advantages. Specifically, the highest MRR) achieved with the EDM-PSoC system stands at 0.1498 mm³/min, exceeding the highest MRR attained by the EDM-Existing system at 0.1026 mm³/min. Even the lowest MRR value for the EDM-PSoC system, recorded at 0.0752 mm³/min, surpasses the lowest MRR recorded with the EDM-Existing system, which is 0.1348 mm³/min. Moreover, the mean MRR for the EDM-PSoC system is notably higher at 0.1348 mm³/min compared to the mean MRR of 0.0878 mm³/min for the EDM-Existing system. Additionally, the lower standard deviation of 0.0071 for the EDM-PSoC system, contrasted with 0.0077 for the EDM-Existing system, signifies higher consistency in MRR values, underlining its stability and reliability at the 6 A current setting. These precise numerical comparisons further underscore the superior performance and reliability of the EDM-PSoC system in material removal efficiency at higher current settings.

In conclusion, the comparative analysis across different current settings (2 A, 4 A, and 6 A) highlights the consistent superiority of the EDM-PSoC system over the EDM-Existing system in terms of material removal efficiency and stability. At all current settings, the EDM-PSoC system demonstrates higher MRR values, indicating its ability to remove material at a faster rate and thus enhance productivity in machining operations. Moreover, the EDM-PSoC system consistently exhibits higher mean MRR values, further underscoring its overall enhanced efficiency in material removal. At the 2 A current setting, while both systems show comparable efficiency in managing material removal, the EDM-PSoC system outperforms the EDM-Existing system, particularly in handling longer ignition time delays and achieving superior MRR values. Moving to the 4 A current setting, the performance gap between the two systems widens, with the EDM-PSoC system demonstrating significantly higher MRR values and greater stability in performance. Finally, at the 6 A current setting, the superiority of the EDM-PSoC system remains pronounced, with substantial improvements in MRR values and consistency compared to the EDM-Existing system. The consistently superior performance of the EDM-PSoC system across different current settings underscores the effectiveness of advanced technologies, such as PSoC, in optimizing EDM processes and enhancing machining efficiency. These findings suggest that the integration of PSoC technology enables the EDM-PSoC system to achieve higher material removal rates, maintain stability in performance, and effectively manage challenging machining conditions. Consequently, the EDM-PSoC system holds significant promise as a preferred solution for various industrial applications requiring precise and efficient material removal processes. Overall, these comparative results contribute to advancing the understanding of EDM technology and highlight the potential for further optimization and innovation in EDM systems.

Overall, the comparative study between the EDM-PSoC and EDM-Existing systems highlighted significant performance improvements in ignition time delay and MRR. At the 2 A current setting, the EDM-PSoC system achieved a 39% reduction in ignition time delay compared to the EDM-Existing system, with similar reductions of 40% at 4 A and 21% at 6 A. Additionally, the EDM-PSoC system demonstrated superior material removal efficiency across all current settings. For instance, at 2 A, the highest MRR of the EDM-PSoC system was 0.0153 mm³/min, surpassing the EDM-Existing system's 0.0115 mm³/min. This trend continued at 4 A and 6 A, with the EDM-PSoC system achieving higher MRR values of 0.0616 mm³/min and 0.1498 mm³/min respectively, compared to 0.0460 mm³/min and 0.1026 mm³/min for the EDM-Existing system. These consistent improvements in MRR with 51% at 2 A, 41% at 4 A, and 54% at 6 A underscored the enhanced efficiency and stability of the EDM-PSoC system. These findings suggest that the EDM-PSoC system offers a more effective and reliable solution for precision machining, with the potential to significantly reduce machining time and optimize operational costs.

The potential impact of these findings on the field of EDM is considerable. The integration of advanced technologies, such as the PSoC microcontroller, into EDM systems can lead to more precise, efficient, and reliable machining processes. This can drive innovation and optimization in EDM applications, making the EDM-PSoC system a preferred solution for industries requiring high precision and efficiency in material removal processes. The improvements in performance and stability can contribute to higher productivity, cost-effectiveness, and overall advancement in EDM technology.

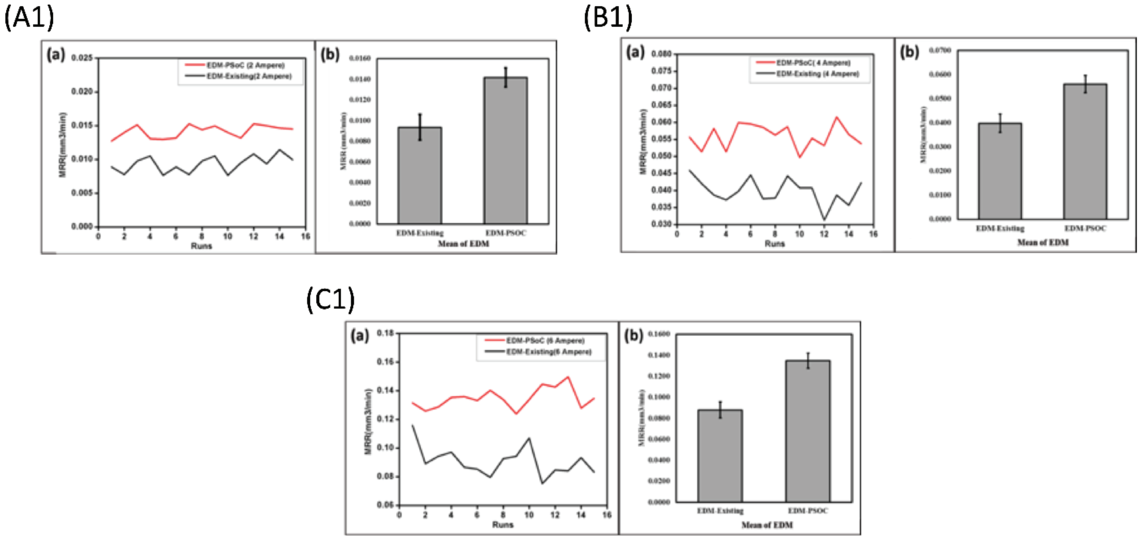

FIGURE 7. Comparison average time delay between EDM-PSoC system and EDM-Existing system for:
(a) 2 A, (b) 4 A, and (c) 6 A of current settings

CONCLUSION

In summary, this research introduced and implemented an innovative EDM system by integrating a PSoC microcontroller. The development included pulse generator control, voltage gap regulation, timer functions, and flushing system. The experimental studies demonstrated significant improvements in ignition time delay and MRR compared to the existing EDM system. The EDM-PSoC system consistently outperformed, showcasing a 39% reduction in ignition time delay at 2 A, 40% at 4 A, and 21% at 6 A, along with notable increased in MRR by 51%, 41%, and 54%, respectively. These advancements suggest enhanced machining efficiency, with potential benefits for reduced machining time and optimized costs. The integrated EDM-PSoC system represents a notable technological advancement with practical implications for precision machining applications. Future research could explore further enhancements in the EDM-PSoC system, such as optimizing the microcontroller algorithms for different machining conditions and materials. Additionally, investigating the integration of other advanced technologies, like artificial intelligence and machine learning, could further improve system adaptability and performance. Exploring these directions can lead to even greater efficiency and precision in EDM applications, solidifying the EDM-PSoC system's role as a cutting-edge solution in the industry.

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DECLARATION OF COMPETING INTEREST

None.

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