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Review

Electrical Discharge Machining of Composites: A Critical Review of Challenges and Innovations

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Abstract: Electrical Discharge Machining (EDM) is a critical non-conventional manufacturing technique for shaping electrically conductive materials, especially those with high hardness or complex geometries. Utilising thermal energy generated by controlled electrical discharges, EDM enables precise material removal without mechanical contact. This review systematically examines recent advancements in EDM with a focused lens on composite materials, specifically Metal-Matrix Composites (MMCs), Polymer-Matrix Composites (PMCs), and Ceramic-Matrix Composites (CMCs), which present distinct challenges due to their heterogeneous structure and limited machinability using conventional methods. This study investigates the influence of both electrical and non-electrical parameters on key performance indicators, including Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface integrity. Notably, hybrid approaches such as Powder-Mixed EDM and cryogenic-assisted EDM demonstrate significant potential in enhancing machining performance and extending Tool Life (TL). By synthesising over two decades of research, this review identifies critical trends, technological innovations, and ongoing challenges in the EDM of composites. The findings emphasise the importance of parameter optimisation and novel dielectric modifications in advancing the efficiency, precision, and sustainability of EDM processes. This work provides a timely and comprehensive perspective on the evolving landscape of composite machining, outlining directions for future research in adaptive and hybrid EDM technologies.

Keywords: composite materials; EDM performance parameters; material removal rate; tool wear rate; surface integrity; advanced manufacturing techniques

1. Introduction

EDM is one of the most widely used non-conventional machining methods, and it is mainly used to machine electrically conductive parts, regardless of their hardness, giving it a marked advantage in manufacturing moulds, dies, and components for the automotive, aerospace, and surgical sectors where parameter optimisation is paramount [1]. Teimouri and Baseri [2] utilised a rotary tool integrated with a rotating magnetic field to improve the efficacy of debris removal from the machining zone in the EDM process. They developed two Adaptive Neuro-

Fuzzy Inference System (ANFIS) models aimed at establishing a relationship between various EDM parameters and the outcomes of Material Removal Rate (MRR) and Surface Roughness (SR), drawing on data acquired from experimental observations. In addition, EDM avoids direct mechanical interactions between the electrode and the workpiece [3,4], thus eliminating mechanical stresses, vibrations, and associated problems during the machining process [5,6]. Figure 1 illustrates how material removal in EDM is conducted based on the erosion of electrical discharges between two electrodes: the tool and the workpiece. Various theories have been proposed to elucidate the complex phenomenon of "spark erosion" [7–9].

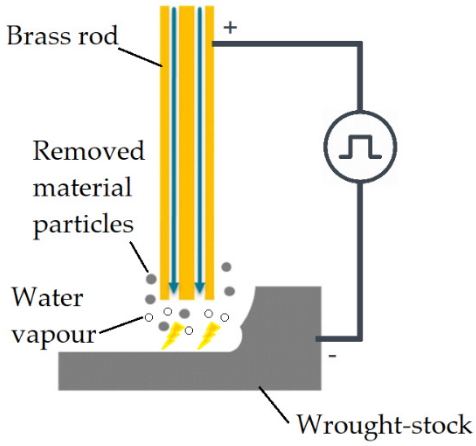

Figure 1. Schematic of the EDM discharge process and material removal [10].

There are some forms of EDM where micro-EDM, penetration EDM, and wire-cut EDM [11,12] are included. Tong, et al. [13] emphasised the effects of pulse duration, peak current (I_p), machining polarity, track style, track overlap, and scanning velocity on the 3D micro electrical discharge machining (3D SSMEDM). Pulse duration and I_p were decisive parameters for efficiency and stability. The cathode processing achieved ~60% of the MRR compared to anode processing, and the optimised parameters allowed the fabrication of complex 3D microstructures. Liu, et al. [14] introduced the concept of "scale effects" concept to distinguish between micro and macro EDM performance and suggested a theory as a suitable evaluation method for optimising micro EDM parameters. Tiwary, et al. [15] combined Response Surface Methodology (RSM) and a fuzzy Technique for the Order of Preference by Similarity to the Ideal Solution (TOPSIS) to optimise pulse-on time (T_{on}), I_p, voltage gap (V_g), and flush pressure (F_p) for selection of micro-EDM process parameters. Wire Electrical Discharge Machining (WEDM) is a variant of Electrical Discharge Machining (EDM) that employs a thin, consumable wire as the electrode, making it particularly effective for producing intricate and delicate components, such as medical devices and electronic equipment [16].

On the other hand, the Modulated Short Electric Arc Machining (MSEAM) process utilises a modulated electric arc to remove material from the workpiece and is applied for high-speed machining (HSM) of materials that are challenging to machine. High-frequency electrical discharge-assisted milling (HF-EDAM) is a novel machining process investigated by Xu, et al. [17], suitable for hard and brittle materials such as Metal-Matrix Composites (MMC) [18], which combines EDM and milling to remove material from a workpiece. Abdudeen, et al. [19] reviewed recent advancements in Powder-Mixed Electrical Discharge Machining (PMEDM), focusing on the maximum Material Removal Rate (MRR), Tool Wear (TW) reduction, and Surface Roughness (SR). Studies indicate significant enhancements in EDM efficiency by mixing conductive powders into the dielectric fluid, especially with optimised powder concentration, I_p, and pulse settings. It has proven effective for machining hard materials like MMCs and insulating ceramics, with applications in micro-machining and die-making [20].

This manufacturing process is characterised by its effectiveness in precisely removing material and is widely used in various industrial applications. The quality assessment for high precision and accuracy is not only measured by the controlled electrical discharges between the electrodes but also by the material removal rate (MRR) and arithmetic mean surface roughness (Ra). These parameters are directly concerned by the Heat-Affected Zone (HAZ) on metal and wire electrode meeting points [21], playing a crucial role in the efficiency and quality of this manufacturing process. Works by the lights of Sudhakara and Prasanthi [7] and Aspinwall, Dewes, Burrows, Paul and Davies [8] detail studies on current density and theories related to the "erosive spark" phenomenon in the context of Electrical Discharge EDM. The EDM process parameters can be divided into electrical and non-electrical (Figure 2).

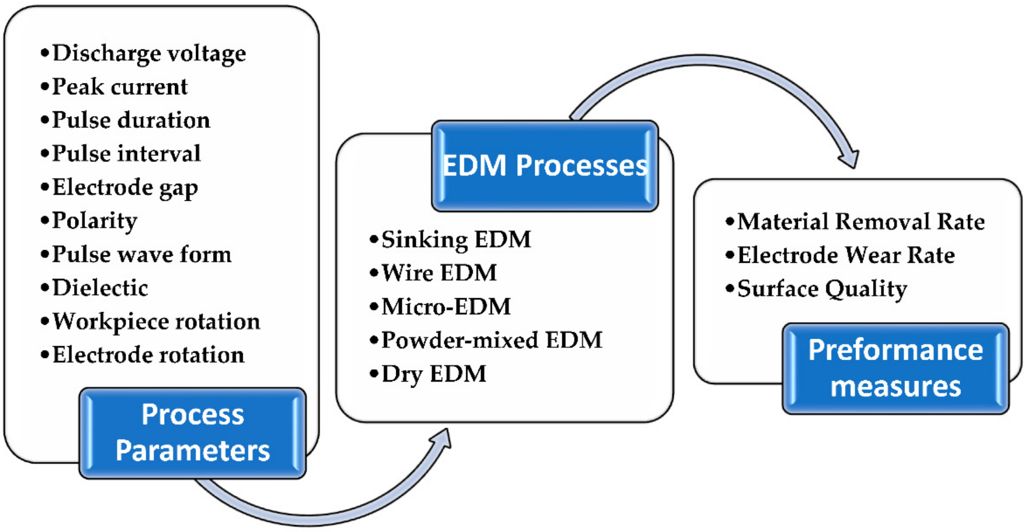

Figure 2. The processes of EDM and their process parameters and performance measures [22].

The main electrical parameters are discharging voltage, I_p, pulse duration, voltage gap (V_g), polarity, pulse waveform, duration and interval:

1. **Discharge Voltage:** Related to the opening of the spark and the resistance to rupture of the dielectric fluid. Increasing the voltage creates an ionisation path between the workpiece and the electrode, helping to stabilise the cut [23,24],
2. **I_p:** Considered the most significant parameter in the EDM process. It varies during each pulse and is crucial for roughing and deburring operations with a large surface area [24–26],
3. **Pulse Duration:** Determines the working time and frequency of the process, characterised by Pulse-on time (T_{on}) and Pulse-off time (T_{off}). MRR is directly related to the energy applied during the pulse duration [24,27,28],
4. **V_g:** Vital for cutting stability, it is defined by the tool's servo mechanism [24,29],
5. **Pulse Polarity and Waveform:** These can be positive or negative, determined by experience and factors such as tool material, work material, and current density. Modern sources can insert oscillation pulses to prevent arcing [24],
6. **Pulse duration:** Influences the depth of the HAZ and the remelted layer. After an optimum value, the MRR decreases [27],
7. **Pulse interval:** Affects machining speed and cutting stability. A shorter interval results in faster machining. However, if it is too short, the ejected material may not be washed away efficiently by the dielectric fluid, resulting in spark instability and erratic cycles [29].

The main non-electrical parameters in the EDM process include dielectric fluid F_p washout, workpiece, and electrode rotation. These parameters are fundamental in optimising performance measurements [30,31].

1. **Dielectric fluid F_p:** Studies on F_p indicate its influence on SR, Electrode Wear Rate (EWR) [32], cooling function, and debris removal during the machining process [30,31]. Experimental results have shown that F_p affects the MRR and EWR during roughing, while in the finishing operation, it influences the Surface Smoothing Rate (SSR) [30]. Both the TMR and EWR increased with increasing wash pressure. Washing pressure also impacts crack density and the remelted layer, which can be minimised by obtaining an optimum washing rate based on empirical data,
2. **Workpiece rotation:** Rotating the workpiece improves the circulation of the dielectric fluid in the workpiece, contributing to a more uniform Temperature (T) distribution. This results in better MRR and SR [33,34],
3. **Electrode rotation:** Electrode rotation, also known as electrode rotation, provides a more effective washing action and improves spark efficiency [35]. Consequently, an improvement in MRR and SR has been observed due to the effective washing of the gap provided by electrode rotation [36–38].

However, understanding and controlling these electrical and non-electrical parameters is crucial to optimising the efficiency and reliability of the EDM process. Table 1 presents the parameters that influence EDM.

Table 1. Performance Parameters.

Performance Measures	Information
MMR	MRR is a performance measure for the erosion rate of the workpiece and is typically used to quantify the speed at which machining is carried out. It is expressed as the volumetric amount of workpiece material removed per unit time [39–41].
EWR	EWR is a performance measure for the erosion rate of the tool electrode and is a factor commonly considered when considering the geometrical accuracy of the machined feature. It is expressed as the volumetric amount of tool electrode material removed per unit time [42–44].
Wear Ratio (WR)	WR is the ratio of EWR/MRR and is used as a performance measure for quantifying tool-workpiece material combination pairs since different material combinations give rise to different EWR and MRR values. A material combination pair with the lowest WR indicates that the tool-workpiece material combination gives the optimal EWR and MRR condition [45,46].
SR	SR is a broad performance measure used to describe the condition of the machined surface. It comprises output parameters such as the extent of HAZ, recast layer thickness and micro-crack density [47–49]. It is a classification of surface parameters used to describe an amplitude feature, which translates to the roughness of the surface finish. Of the many parameters available to quantify SR, the most used in EDM are Ra, maximum peak-to-valley surface roughness (Rmax), and root mean square surface roughness (Rq) [50–52].

EDM processes offer a variety of approaches to material removal in industrial applications, standing out for their fundamental role in the manufacture of complex parts. One of these methods is Sie-Sinking EDM, in which the workpiece is shaped by a preformed electrode tool or by the three-dimensional movement of a simple electrode, like milling. The materials commonly used for the electrode are Copper (Cu) or graphite (Carbon, C), while the numerical control monitors the opening conditions, such as voltage and current, synchronising the different axes and the pulse generator. Filtration of the dielectric liquid is essential to remove debris and particles from the process [53]. Another relevant technique is WEDM, in which the material is eroded by discrete sparks between the workpiece and a continuous wire, typically made of thin Cu. Wide applications are found in sectors such as the tool and mould industry, medicine, electronics, and the automotive industry. This method enables the machining of complex shapes to a high degree, eliminating the need for pre-moulded electrodes [54].

Ultimately, Micro-EDM distinguishes itself by its capability to machine micro-holes, micro-axes, and intricate 3D micro-cavities. With four primary variations, including micro-EDM, micro-sink EDM, micro-EDM drilling, and micro-milling EDM, this process is crucial for applications that require extreme precision, such as the production of electronic and medical components [53]. These methods represent significant advances in modern manufacturing, providing versatile solutions to complex machining challenges. In addition to the methods mentioned, it is vital to emphasise that EDM has other less widespread but equally relevant techniques. Two approaches are Powder Mix EDM and Dry EDM [55].

Composite materials are recognised for their superior mechanical properties compared to unreinforced alloys [56]. However, the full implementation of these advanced materials is limited by the high cost associated with machining, representing a significant challenge (Figure 3) [57]. The main obstacle to overcoming re-sides is the unsatisfactory service life of the devices and the subsequent sub-surface degradation of the composites when machined by conventional methods [58]. This study investigates the feasibility of applying EDM to composite materials [59,60] as a promising alternative [61]. It is important to emphasise that composites are frequently used as electrode materials today [39,62]. This approach could pave the way for innovative solutions, overcoming the challenges associated with machining composites and potentially improving the durability and performance of devices made from these advanced materials. Lau, et al. [63] conducted a study to assess the feasibility of employing EDM for producing Carbon Fibre Reinforced Polymers (CFRP). The optimal MRR value was identified by varying I_p and T_{on}; however, it is recommended that EDM of CFRP be performed at low current density, as high current density may cause the epoxy resin to smear over the surface. Cu electrodes outperformed graphite electrodes in TW, and tools with positive polarity yield a higher MRR and EWR.

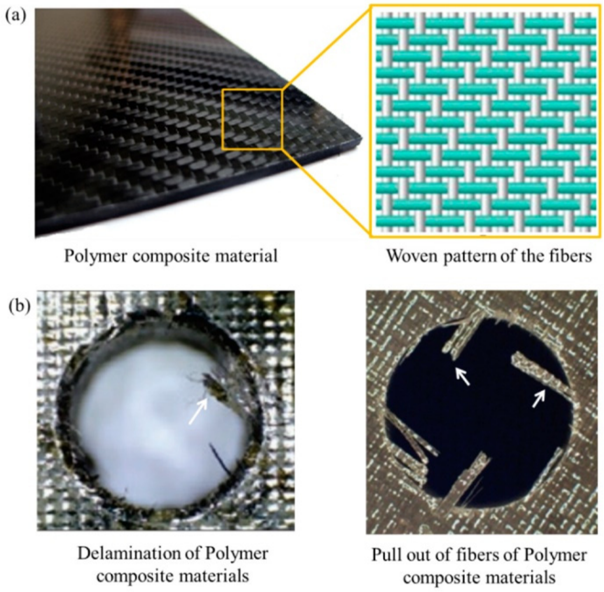

Figure 3. (**a**) Polymer composite materials and woven patterns of fibres of the reinforcement phase; and (**b**) delamination and pull out of fibres during the drilling of polymer composite materials [64].

MMCs are an advanced category of materials integrating ceramic reinforcements within a metallic matrix, yielding superior properties such as high stiffness, fatigue strength, and wear resistance compared to conventional alloys [65]. These properties make MMCs highly desirable in the aerospace, automotive, and defence sectors. The choice of matrix and reinforcement materials, as well as their dispersion and bonding, critically influences the composite's mechanical behaviour, allowing tailored properties to suit specific applications [66,67]. However, machining MMCs presents significant challenges, as conventional methods often lead to rapid TW and subsurface degradation, limiting their full implementation [68]. Figure 4 depicts a scheme of a novel EDM approach in MMC, which includes the ejecting-explosion phenomenon. Kar, et al. [69] compiled key aspects for the commercialisation of Aluminium-Based Metal Matrix Composites (AMMC), including cost reduction, engineering design, and process monitoring. Also, the reinforcement directionality and particle characteristics are crucial for mechanical performance. Continued Research and Development (R&D) are essential for advancing AMC development, such as novel architectures (e.g., foam structures) for thermal management and protection applications, and shape memory and magnetic metals are promising for multifunctional MMCs. Chen, et al. [70] conducted a comprehensive review of the machining performance of SiC/Al MMC composites, employing both Conventional Machining (CM) techniques and non-conventional methods, including EDM, powder-mixed EDM, WEDM, among others. This study provided an in-depth overview of the machining characteristics of SiC/Al MMC composites across diverse processing methods and established optimised EDM parameters to serve as a reference for industrial applications. Sarala Rubi, et al. [71] conducted a comprehensive review of a broad spectrum of investigations spanning WEDM and various EDM process variants. The study highlights WEDM research that emphasises the optimisation of process parameters and evaluates multiple factors influencing machining efficiency and dimensional accuracy. Also, Rubi, et al. [72] investigated the application of Wire Electrical Discharge Machining (WEDM) on LM6/fly ash composites, aiming to optimise key process variables to achieve maximum material removal rate (MRR) and minimum surface roughness (SR). The study employed Taguchi's L27 orthogonal array design of experiments, grey relational analysis, and analysis of variance (ANOVA) to systematically determine the optimal settings for enhancing both performance measures.

Lastly, Ceramic Matrix Composites (CMCs) are advanced materials extensively used in aerospace and energy sectors due to their exceptional thermal stability and structural resilience [73]. These materials require robust joining techniques, such as permanent and non-permanent joints, between CMC and metal components to meet the high demands of applications like gas turbines and reactor walls [74]. As newer CMCs emerge for high–T uses, ongoing development refines existing joining methods to enhance joint performance and reliability. Machining CMCs, however, pose significant challenges due to their brittle and heterogeneous nature, often resulting in unique thermal and mechanical defects [75].

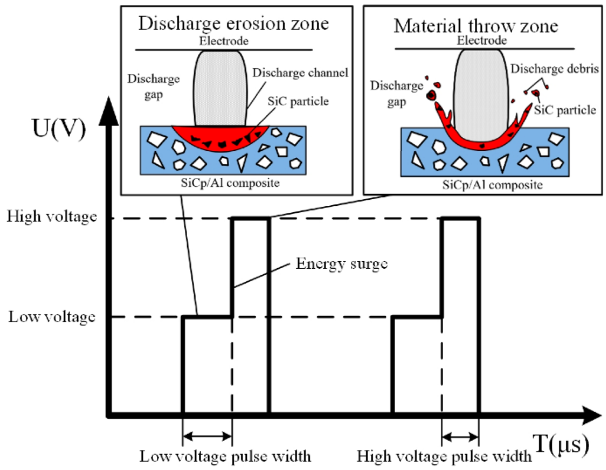

Figure 4. High- and low-voltage composite waveform [76].

Due to CMCs' complex surface properties, machining techniques are continuously optimised (Figure 5) [77,78], enabling reliable, precise production for high-performance applications where safety and structural integrity are paramount.

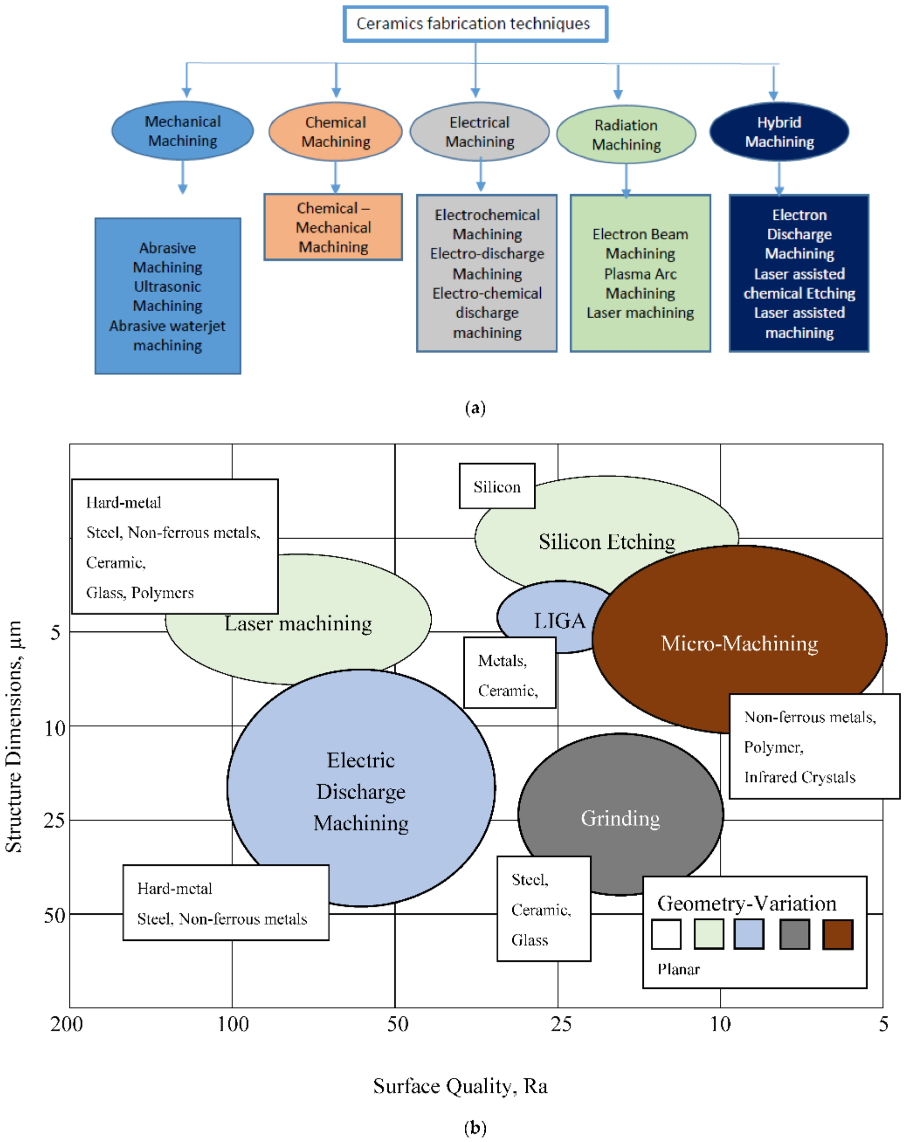

Figure 5. (**a**) Ceramic fabrication techniques, (**b**) EDM and micro-EDM relatively to other manufacturing processes on CMC [77].

While previous studies have explored aspects of EDM performance on composite materials, this review presents a novel and comprehensive synthesis of both conventional and emerging EDM techniques–specifically tailored to the machining of MMCs, PMCs, and CMCs. The work distinguishes itself by systematically correlating a broad set of electrical and non-electrical parameters with critical machining outputs such as MRR, TWR, and Surface Integrity across a wide spectrum of composite systems. Notably, it integrates findings from over two decades of research to map the evolution of parameter optimisation strategies while also incorporating underexplored developments such as powder-mixed dielectrics, cryogenic enhancements, and surface-modified electrodes. This study thus provides a unique, data-driven foundation for future innovations in precision composite machining using EDM.

Section 1 presented a theoretical framework on EDM, its historical background, some variants that may be found, and some of the researchers' discoveries within the composites field. Section 2 details the methodology employed in this study, explicitly using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [79] and the Systematic Literature Review (SLR) [80] to identify pertinent research. In Section 3, the selected papers are rigorously examined to uncover sub-categories within the identified research domains. Section 4 thoroughly discusses the content analysis findings, providing an overview of emerging research themes and challenges associated with the use of EDM composites. Additionally, this section addresses the practical implications and limitations of the study. Finally, Section 5 concisely summarises the essential findings and offers a brief outlook on future research directions, while presenting the conclusions drawn.

2. Method of Research

The systematic review exploration and data-gathering phases were carried out through an SLR, utilising its structured, methodical, and reproducible framework. [81,82], and according to the PRISMA guidelines, to ensure transparency and rigour [83]. The process was conducted using Dimensions.ai, a platform seamlessly integrated with IEEE Xplore, ScienceDirect, Web of Science, Google Scholar, and Scopus databases, offering extensive access to scholarly data. This study critically examines the existing scientific literature on advancements in EDM performance in composites, including MMCs, PMCs, and CMCs, with a focus on the influence of various input parameters. Searches were conducted in bibliographic repositories to build a comprehensive literature database on EDM in composite manufacturing, utilising keywords such as Electric Discharge Machining (EDM), Metal-Matrix Composites (MMCs), Polymer-Matrix Composites (PMCs), Fibre Reinforced Polymers (FRPs), and Ceramic-Matrix Composites (CMCs). This review examines the impact of EDM parameters on outcomes, including Material Removal Rate (MRR), Surface Finish, Tool Wear Rate (TWR), and Surface Integrity.

2.1. Search Strategy

An extensive literature search was conducted from January 2025 across multiple electronic databases, including IEEE Xplore, ScienceDirect, Web of Science, Google Scholar, and Scopus. The search was limited to articles published between 2000 and 2024 to capture the evolution and latest advancements in EDM for MMCs, PMCs, and CMCs. Keywords used were:

- "Electric Discharge Machining" OR "EDM",
- "Composites" OR "Metal-Matrix Composites" OR "Polymer-Matrix Composites" OR "Fibre Reinforced Polymers "OR "Ceramic-Matrix Composites",
- "Process Parameters" OR "Material Removal Rate" OR "Tool Wear Rate" OR "Surface Finish"

Each database's Boolean operators and specific syntax were applied to refine search results.

2.2. Inclusion and Exclusion Criteria

Studies were selected based on the following criteria:

- Inclusion Criteria:
    - Peer-reviewed journal articles focusing on EDM in MMCs, PMCs, or CMCs,
    - Studies investigating the effects of EDM parameters (e.g., Ip, Ton, Toff, and dielectric type) on outcomes like MRR, TWR, surface roughness, integrity,
    - Articles published in English.
- Exclusion Criteria:
    - Patents and editorials,
    - Studies focusing exclusively on other non-traditional machining techniques,
    - Articles lacking quantitative analysis of EDM parameters,

2.3. Study Selection

Two independent reviewers screened titles and abstracts using the inclusion and exclusion criteria. Disagreements were resolved through discussion; if unresolved, a third reviewer made the final decision. Full texts of selected articles were retrieved and assessed for eligibility, and reasons for exclusion were documented.

2.4. Data Extraction

A standardised data extraction form was developed, recording information such as:

- Study characteristics: authors, year, and country.
- Composite material type (MMC, PMC, or CMC).
- EDM parameters investigated (e.g., Ip, Ton, and Toff).
- EDM outcomes measured (e.g., MRR, TWR, and SR).
- Critical findings on parameter influence and optimal settings.
- Risk of Bias Assessment,
- The risk of bias for each study was evaluated using a modified Newcastle-Ottawa Scale (NOS) [84] tailored for engineering studies. Each study was assessed on the basis of selection criteria, comparability, and outcome reporting, with scores indicating low, moderate, or high risk of bias.

2.5. Data Synthesis

Results were synthesised by composite type (MMC, PMC, and CMC) and analysed based on the influence of EDM parameters. A qualitative synthesis summarised trends, optimal parameter ranges, and parameter impact on EDM performance across composite categories. Quantitative data (means and standard deviations) were pooled when appropriate, and effect sizes were calculated to compare the impact of EDM parameters on different composites. The resulting 51 papers addressed within Section 3 can be categorised into distinct thematic areas. Based on the analysis from Dimensions.ai, the articles can be classified into various subjects, as outlined below and illustrated in Figure 6:

- Engineering (40),
    - Aerospace Engineering (4001),
    - Manufacturing Engineering (4014),
    - Materials Engineering (4016),
- Information and Computing Sciences (46),
- Mathematical Sciences (49).

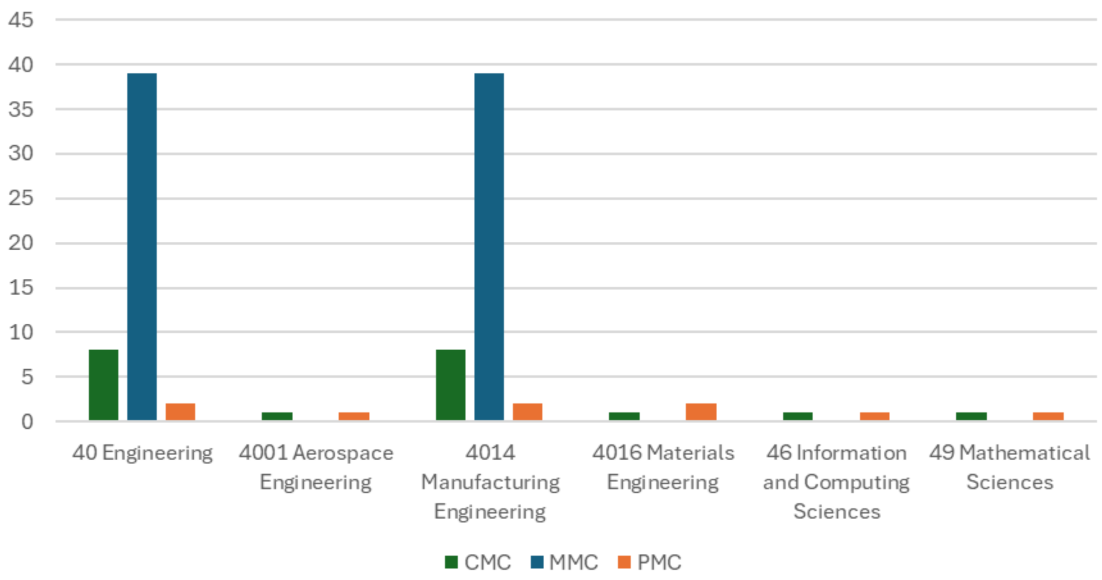

Figure 6. Categorisation of papers addressed in the review about EDM applied to CMCs, MMCs and PMCs.

Section 3 offers an in-depth review of the literature on EDM as applied to composite materials. This concise overview of the manufacturing process, particularly its application to composites, whose use has increased significantly over recent decades, aims to provide a systematic summary for both novices and experienced practitioners. The methodological approach is centred on its relevance to advanced metalworking industries. A meticulously organised and systematic presentation of the information is vital for fostering a deep and comprehensive understanding of the topic. Moreover, its substantial contributions to the field underscore the significance of this research.

3. Literature Review

Table 2 presents several papers from 2000 to 2024, along with their respective techniques and main results, which apply the EDM technique. This compilation provides a valuable and comprehensive insight into the evolution of manufacturing processes used for composites.

Table 2. Studies carried out on composite engineering materials.

Ref	Material	Technique	Highlights
[85]	Al2618—20% SiC and A356–35% SiC MMC	Taguchi L_{27}, ANOVA	/ EDM is suitable for Particle Reinforced MMC (PRMMC); it is a slow process with a crater-like surface, / Laser machining is productive but of poor quality; thermal changes were observed, / Abrasive Water Jet Machining (AWJM) is suitable for rough cuts, no thermal damage, and rougher SR.
[86]	Al6061—10% Al_2O_3 MMC	Taguchi L_9	/ EDM of Blind-hole Drilling (BhD) is feasible for Al6061—10% Al_2O_3 MMC machining, / Electrical parameters significantly impact the EDM process over non-electrical parameters, / Semi-empirical expressions simplify the evaluation of MRR, EWR, and SR.
[87]	AlSi7Mg—20% SiC and AlSi7Mg—20% Al_2O_3 MMC	Taguchi L_{18}, ANOVA	/ The most significant parameters influencing surface characteristics are abrasive size, abrasive concentration, and I_p.
[88]	Al356-T6—15% SiC MMC	RSM	/ The more significant the Pulse-off time (T_{off}) displacement, the lower the EWR value. On the other hand, for any voltage value, EWR increases with increasing I_p and T_{on}.
[89]	Al-alloy—20% and 25% SiC MMC	Taguchi L_8, ANOVA	/ Positive polarity increased MRR, leading to a higher MRR on the brass electrode, / EWR decreased with a lower SiC percentage and increased with the current, / SR decreased with lower pulse current; increased with SiC percentage.
[90]	Al-alloy—10% SiC MMC	Grey Relational Analysis (GRA), ANOVA	/ GRA optimised multi-response characteristics in EDM for improved results, / Simplified optimisation process by converting multi-response variables to single response.
[91]	Al6025—20% and 25% SiC MMC	Taguchi L_9, ANOVA	/ EDM drilling Al-SiC composites with the tube electrode was evaluated and found feasible.
[92]	Si_3N_4—37.5 and 40% TiN CMC	Taguchi L_{27}, ANOVA	/ Silver coating improves productivity and SR uniformity, / Clamping positions affect cutting velocity and SR, / Silver paint significantly increases cutting velocity and productivity.
[93]	Al4Cu6Si—10% SiC MMC	Design of Experiments (DOE), RSM, ANOVA	/ The MRR-based mathematical model aligns with experimental values at a 95% confidence level, / Key cycle parameters affecting MRR are I_p and T_{on}, / SEM analysis showed an improved surface finish with lower RLT in the average input method.
[94]	Al6061—20% Al_2O_3 MMC	GRA	/ The discharge current is crucial in determining the surface finish and MRR.

[95]	Al-alloy—5% SiC—5% B_4C and Al-alloy—5% SiC—5% $Glass_p$ MMC	Genetic Algorithm	/ Ceramic reinforcements make EDM machining of Al-SiC composites difficult, / Combine parameters for optimal MRR and SR.
[96]	ZrO_2—WC MMC	Parametric experimental study	/ I_p increases both MRR and SR, as they enhance the discharge energy and melting of the material, / T_{on} increase extends the duration of material heating, leading to higher MRR, but also increases SR due to a larger HAZ, / Longer T_{on} allows for better cooling of the workpiece, reducing SR but lowering the overall MRR.
[97]	Al 359—20% SiC MMC	A parametric experimental study with modelling	/ Breakdown voltage predicted between 26.2–34.2 V—Spark action confirmed as arc-based, / Increased I_p, T_{on}, T_{off}, and electrolyte concentration promote arcing.
[98]	Al alloy—2.5% and 5% TiC MMC	Taguchi L_{18} ANOVA	/ Higher TiC concentration reduces MRR due to particle shielding effect, / Optimal parameters include I_p and F_p, / Recast layer thickness increases with TiC content.
[99]	Al7075—B_4C MMC	RSM	/ Optimal parameters include high pulse current and voltage for maximising MRR, / T_{on} significantly impacts TW, / Surface finish deteriorates with higher MRR.
[100]	ZC63/SiC MMC	Taguchi L_{27}	/ Simultaneous optimisation of multiple WEDM responses (MRR, SR, WWR, Kw, WLT). / Optimal settings: particulate size 25 µm, T_{on} = 6 µs, wire tension 1 g. / SEM validation confirmed enhanced quality.
[101]	Al alloy—40% SiC MMC	Parametric experimental study	/ PMEDM lowered SR by 31.5%, wear resistance was 2× better than EDM, increased microhardness by 40% and enhanced corrosion resistance.
[102]	Al alloy—10% SiC MMC	Lexicographic Goal Programming (LGP), ANOVA	/ LGP optimised results for both rough and finish machining, / Rough machining optimal parameters are I_p = 16 A and T_{on} = 10 µs, / MRR increases with I_p but decreases with an increase in T_{on}.
[103]	Al6063—10% SiC MMC	RSM	/ Optimal parameters are 3 < I_p < 15 A, 30 < T_{on} < 150 µs and spindle speed (*s*) of 300–700 rpm, / MRR increases with discharge current and arc on time. / TW reduces as T_{on} increases, / EDD provides higher MRR than EDM but results in higher TW.
[104]	Al 6061—25% SiC MMC	Taguchi L_{27}, ANOVA, ANFIS-ABC	/ T_{on} and I_p significantly affect V_c and SR, / Optimal results were obtained with O_2 gas, brass wire for high V_c, T_{on} = 126 µs, I_p = 230 A, Wire Feed (WF) of 12 m/min, Wire Tension (WT) of 12 g, and V_g = 20 V, / ANFIS-ABC optimisation showed superior performance.
[105]	A356.2—65% SiC Al-alloy—10% SiC and 5% quartz A359—30% SiC MMC's	Taguchi L_{27}	/ Graphite mixed dielectric enhances microhardness significantly, / Material with 65% SiC showed the highest microhardness (486.24 HV), / PMEDM improves surface integrity.
[106]	Al-alloy—10% SiC MMC	Parametric experimental study, ANOVA	/ Cryogenic cooling reduced electrode TW by 18%, / SR improved by 29% with cryogenic cooling compared to conventional EDM,

			/ Higher I_p increases TW.
[107]	Al7075/SiC MMC	Taguchi L_{27}, GRA	/ Optimal WEDM parameters derived for MRR, SR, WWR, Kw, and WLT. / T_{on} = 6 µs and wire tension (1 g) were critical. / Validation showed improved surface quality and dimensional accuracy.
[108]	Al2618—0, 2, 4, 6 and 8% AlN, Si_3N_4 and ZrB_2 MMC	Taguchi L_{25}, ANOVA	/ Increased reinforcement improves mechanical properties, / Optimal parameters for EDM: I_p = 30 A, T_{on} = 7 µs, / - Enhanced hardness and tensile strength (σ_u).
[109]	Si_3N_4—TiN CMC	Taguchi L_{25}, GRA	/ Key parameters: I_p, T_{on}, and V_g, / Optimal settings improved MRR, reduced TWR, and enhanced geometric tolerances.
[110]	Al2618—0, 2, 4, 6 and 8% AlN, Si_3N_4 and ZrB_2 MMC	Taguchi L_{25}, ANOVA, Genetic Algorithm	/ Elevated T enhanced MRR and depth but increased TWR, / Optimal conditions were I_p = 30 A, T_{on} = 7 µs and T = 350 °C.
[111]	Al4032—0, 2, 4, 6 and 8% ZrB_2 and TiB_2 MMC	Taguchi L_{25}, ANOVA	/ Optimal parameters: Higher T_{on} and current improve MRR and depth, / Mechanical strength increased with reinforcement content, / Cu tool used in EDM.
[112]	Al6061—10% SiC and 2.5% TiB_2 MMC	RSM, Central Composite Design (CCD)	/ Optimal parameters: I_p = 8 A, T_{on} = 70 µs, and no Al powder for high MRR = 171.41 mg/min, / For low TWR: I_p = 2 A, T_{on} = 30 µs, and Al powder with 4 g/L, / For best surface finish of Ra = 3.79 µm, I_p = 2 A, T_{on} = 30 µs, and high powder concentration of 4 g/L.
[113]	Al6061—10% SiC MMC	Parametric experimental study	/ Wire deformation varies with SiC particle size, / Larger particles increase TW, lowering wire durability, / SEM analysis showed deformation along the wire cross-section.
[114]	Al_2O_3—0, 2.5, 5, 7.5, 10 and 12.5% Multi-walled CNT CMC	Parametric experimental study	/ Higher MWCNT improves MRR but increases SR, / Spalling occurs at high I_p, while melting occurs at low I_p, / A porous recast layer and micro-cracks were observed.
[115]	Al-alloy—12% SiC MMC	RSM, Particle Swarm Optimization (PSO)	/ Optimal parameters for PMEDM: low V_g and I_p, longer T_{on} and high F_p, / PSO confirms high MRR, low TW and SR, / Confirmatory tests showed minimal error.
[116]	Glass FRP (GFRP) PMC	Taguchi L_9	/ Optimal inputs for higher MRR: Higher electrolyte concentration of 110 g/L, V_g = 70 V, inter-electrode gap of 120 mm. / ECDM achieved high precision for micro-holes.
[117]	CFRP PMC	Taguchi L_9, ANOVA	/ Optimal parameters for max MRR: V_g = 100 V, 100 pF of capacitance, and s = 1500 rpm, / Achieved a high aspect ratio of 10.9 for micro-holes with W tool.
[118]	CFRP PMC	Grey Fuzzy Logic	/ Optimal Parameters were T_{on} = 150 µs and V_g = 150 V for minimum TW, / Capacitance (63.58%) was the most influenceable parameter, followed by T_{on} (29.17%), Ultrasonic V_g (2.76%), / SEM images showed burr-free surfaces; the EDS spectrum detected carbon in the brass tool due to a deburring process.
[119]	Al7075—6% Red Mud* MMC	CCD, ANOVA	/ I_p and T_{on} significantly impact MRR and TWR,

			/ Optimal results for EDM with enhanced MRR and accuracy.
[120]	Al-alloy—10% SiC and 10% TiC MMC	Parametric experimental study, TOPSIS	/ Optimal WEDM settings included oil + wax + paraffin dielectric boosts kerf width, MRR, and SR, / Surface morphology showed increases in stress and corrosion resistance.
[121]	SiC—Carbon Fibre (CF) CMC	Parametric experimental study	/ EDM efficiently removes Cf-SiC through brittle fracture, / High thermal stress is vital for material removal, with SEM showing crack-induced removal on the SiC matrix and CF.
[122]	Al6351—15% SiC MMC	Parametric experimental study	/ Key EDM parameters: V_g, I_p, T_{on} and T_{off} impact speed, TW, and SR, / - SEM shows high integrity of machined surfaces, confirming EDM suitability.
[123]	A356.2—35% SiC Al-alloy—10% SiC and 5% quartz MMCs	Taguchi L_{18} with Analytic Hierarchy Process (AHP)	/ Optimised EDM parameters focus on metal erosion rate, SR, and residual stresses, / Found that using Cu electrodes results in improved SR and MER compared to graphite, / I_p, T_{on} and T_{off} were critical for managing residual stress and minimising surface defects.
[124]	Al-alloy—35% SiC MMC	RSM with Support Vector Regression-Particle Swarm Optimization (SVR-PSO)	/ Micro-WEDM has shown to be effective for high-volume SiC composites, addressing wire rupture issues, / MRR increases with higher T_{on} and WT, / Ra is minimised with optimised WF and T_{off}, / The SVR-PSO hybrid approach yielded high precision and reliable, optimal parameters for machining speed and surface quality.
[125]	Si_3N_4—TiN CMC	GRA with Teaching-Learning-Based Optimization (TLBO) and TOPSIS	/ Identified that I_p and T_{on} are the most significant factors for improving MRR and reducing EWR, / Optimal EDM parameters are I_p = 10 A, T_{on} = 8 µs, which significantly enhanced MRR, geometrical accuracy and lowered TW, / GRA and TOPSIS effectively balanced MRR, SR, and geometrical tolerances, achieving high machining efficiency.
[126]	Al6092-T6—17.5% SiC MMC	Parametric experimental study	/ MRR peaks at F_p = 12 m/s, it declines beyond, / Higher discharge increases SR by 15–120%, / Optimal hardness achieved with high I_p and low Duty cycle (D_c),
[127]	Al7075-SiC-Mg MMC	Parametric experimental study	/ GAPMEDM (Gas-assisted powder mixed EDM) showed 75% higher MRR, 25% lower EWR compared to REDM (Rotary EDM), / MRR improved by 45% and EWR by 15% over GAEDM (Gas-assisted EDM), / SiC powder concentration of 3 g/l enhances dielectric effects.
[128]	CFRP CMC	GRA, Artificial Neural Network (ANN)	/ Optimum parameters were set as I_p = 4 A, T_{on} = 25 µs, T_{off} = 25 µs, F_p = 6.0 bar, / Negligible burr and low delamination (350.7 µm) under optimal settings, / Uniform circularity (0.979), low taper (−0.81354°), and low TWR (6.9 × 10^{-5} g/min), / The ANN model accurately predicts hole quality beyond set parameter ranges.

[129]	Cermet with 80% WC, 16% Co, 1.5% TiC, 1.0% TaC, 0.5% NbC and 0.2% CrC CMC	Parametric experimental study	/ EDM introduces surface layer altering wear properties, / Optimal finishing reduces altered layer effects, improving wear resistance and reducing friction.
[130]	Al7075—10% B_4C, Al7075—20% B_4C, Al7075—5% B_4C and 5% SiC, and, Al7075—10% B_4C and 10% SiC MMCs	Taguchi L_{18}, ANOVA	/ Optimal MRR achieved at 10% B_4C with I_p = 8 A and 150 min sintering, / Increased B_4C and SiC ratio decreased MRR, / Higher discharge current led to poorer surface quality.
[131]	Si_3N_4—TiN CMC	Taguchi L_{25}, RSM	/ REDM yields a lower recast layer (53–58 µm) vs die-sinking EDM (106–166 µm), / The porosity is higher in REDM but with a smoother finish.
[132]	TiB_2—SiC CMC	Taguchi L_9, ANN with regression analysis	/ Optimal parameters were I_p = 7 A, T_{on} = 2 µs, T_{off} = 11 µs and 17 kg/cm² dielectric pressure, / T_{on}, T_{off}, and WT are key factors for V_c. It increases with T_{on} increases and decreases with T_{off} increases, / - Improved dimensional accuracy, lower EWR, and high MRR, suitable for biomedical use.
[133]	Al7075—6% B_4C MMC	Hybrid DOE Taguchi (Taguchi with GRA and Entropy Weight Method, EWM)	/ Optimal EDM settings were I_p = 140 A, T_{on} = 120 µs, T_{off} = 50 µs, and 0.4 mm gap, / Those settings led to the highest MRR = 0.5628 mm³/min, low TWR, and a good SR.
[134]	Al7075—6% B_4C and 6% SiC MMC	Taguchi L_{27}, RSM, TOPSIS, GRA, EWM	/ Optimized EDM parameters led to 0.42 < MRR < 0.52 mm³/min, 0.0068 < EWR < 0.0103 mm³/min, and 9.19 < Ra < 10.39 µm, / 15% improvement in closeness coefficient, 16% improvement in GRA grade, verified by SEM analysis showing minimal cracks and debris.
[135]	Al2024—2% Al_2O_3, 2% SiC, 2% Si_3N_4, 2% BN MMC	Taguchi L_{18}, NSGA-II, and ANN	/ Achieved highest MRR = 37.84 mm³/min for curved profiles–The lowest Wire Wear Ratio (WWR) occurs at low variable levels, / Optimisation led to up to 76% improvement in MRR and a 16.5% reduction in WWR, showing fewer craters and improved erosion dynamics in high-speed WEDM.
[136]	SiC CMC	Taguchi L_9, S/N ratio, SAF	/ Dry EDM using gases like O_2, N_2, and Air improved MRR by 19.5% and reduced SR significantly, / Highest MRR achieved with O_2, while N_2 produced the smoothest surface by forming a nitride layer, / Introduced Swirl Assisted Flushing (SAF) for faster debris removal, validated by ANOVA, showing I_p and T_{on} as key parameters, with 53.3% and 27% impact on MRR, respectively.

*- On average, red mud comprises up to 65–70% Fe_2O_3, 40–50% Al_2O_3, and 15–25% TiO_2, with variations depending on the source of the bauxite ore.

4. Discussion

This discussion section synthesises the literature's impact, insights, and conclusions, highlighting progress and future research avenues. The influence of essential parameters on the EDM process is a crucial issue for producers and users of this method, seeking to achieve excellent reliability and efficiency [137–141]. The recent literature on EDMing PMCs, MMCs and CMCs demonstrates a notable shift towards enhanced machining. The progressive development of these machining techniques, as documented in recent studies, has significantly expanded the applicability of PMCs, MMCs, and CMCs across high-stakes sectors, including aerospace, defence, and biomedical engineering. This body of work underscores the importance of optimising machining parameters, such as current, pulse-on/off times, and dielectric fluid pressure, which have been shown to influence MRR, SR, and TWR in specific and often complex ways. Such research is instrumental in broadening the adoption of PMCs, MMCs, or CMCs by providing methodologies that mitigate machining challenges, such as subsurface damage, tool wear, and thermal stresses.

Notably, some recent studies present surprising insights, particularly in the realm of dielectric fluid modifications. Research indicates that powder-mixed dielectric fluids can enhance surface quality, hardness, and corrosion resistance while reducing SR significantly compared to conventional EDM fluids. The role of silver coating in improving SR uniformity and productivity in Si_3N_4-TiN CMC machining also introduces a novel approach, indicating that surface modifications to materials may provide advantages in machining efficiency. These findings expand the possibilities for optimised machining in settings where precision and material integrity are critical, offering more flexible methods for controlling surface characteristics and structural outcomes.

The comparative analysis across studies reveals significant differences in performance based on parameter choices and materials. For instance, studies show that higher I_p and T_{on} in EDM enhance MRR and increase SR and TWR, whereas techniques like PMEDM, using a mixed dielectric, yield better hardness and corrosion resistance with reduced SR. Table 3 presents the main parameters of the EDM process and their main influences, while Table 4 summarises the subject with a SWOT analysis of EDM applied to composite materials.

Table 3. Process parameter influence on the EDM process.

Parameters	Influence
Impact of Electrical Impulse Parameters [87]	The parameters T_{on}, I_p, and capacitance play a significant role in defining the sequence of steps to achieve the optimum Gain Voltage (GV) value. When T_{on} and I_p are adequate, and the capacitance is low enough, it is possible to carry out just one GV step to reach the maximum value. Typicaly I_p and voltage increase MRR but can degrade SR and increase TWR due to higher discharge energy.
Frequency Effect [142]	Increasing the number of discharge cycles can affect surface finishes, potentially doubling them with increased current and frequency. Increasing T_{on} raises MRR but can cause a larger HAZ and increase SR; a higher T_{off} reduces TWR but lowers MRR. MRR can double without affecting the finish. I_p is reduced at high frequencies due to inductance, resulting in a decrease in MRR.
Effect of workpiece material [143]	The workpiece's physical, metallurgical, and electrical properties have a significant impact on the EDM method. A lower melting point of the material can improve the MRR, while inadequate heat treatment can lead to distortion and breakage during machining. Positive polarity in EDM increases MRR and optimises machining with brass electrodes. Specific material reinforcement (e.g., SiC) affects TW and SR.
Effect of the structure material [144]	It must have sufficient σ_u for melting and vaporisation, with more excellent resistance to fracture, high electrical conductivity, strong discharge capacity, low melting point, and low energy requirements. Increased SiC or TiC reinforcement in MMCs enhances hardness and wear resistance but lowers MRR—additional reinforcements impact machining by introducing brittleness.
Effect of wire tension [144]	Wire tension improves cutting speed and efficiency and reduces the force of wire vibrations. The wire snaps if the wire tension exceeds the tensile force. Higher wire tension improves cutting stability, reduces deflection, and enhances geometric precision, especially in high-volume applications with high SiC content.
Effect of dielectric fluid and discharge pressure [144]	The dielectric fluid isolates the electrodes until a significant amount of energy accumulates, concentrating the de-charging power in a small region. The discharge pressure is crucial for maintaining a desirable gap state after discharge, enabling the gap to cool, deionise and wash away residues from the workpiece. Without adequate discharge pressure, the machining process does not take place. Increased dielectric pressure enhances flushing, reduces debris, and improves MRR and SR. PMEDM improves microhardness and corrosion resistance.

Table 4. SWOT analysis of EDM in Composite Materials.

	Positive Factors	Negative Factors
Internal factors	Strengths Precision Machining: EDM can achieve high accuracy and intricate detailing, making it ideal for aerospace, automotive, and biomedical applications, No Direct Contact. The non-contact nature of EDM prevents mechanical stresses, reducing the risk of workpiece deformation, Material Versatility: Capable of machining hard and brittle materials, including Metal-Matrix Composites (MMCs), Polymer-Matrix Composites (PMCs), and Ceramic-Matrix Composites (CMCs), Surface Quality Improvements: Hybrid EDM techniques (e.g., Powder-Mixed EDM) enhance surface hardness, reduce residual stress, and improve corrosion resistance, Practical for Tough Materials: Traditional machining struggles with composites, but EDM efficiently processes materials like SiC-reinforced MMCs and CMCs.	Weakness High TW: Electrodes degrade over time, particularly when machining composites with high reinforcement content, Slow MRR: EDM is often slower than conventional machining, making it less efficient for high-volume production, HAZ: Localised thermal damage can lead to micro-cracks and reduced structural integrity, High Operational Costs: The need for specialised electrodes, dielectric fluids, and maintenance increases expenses, Environmental Concerns: The disposal of dielectric fluid and debris generation pose ecological challenges.
External factors	Opportunities Advancements in Hybrid EDM: Emerging techniques like Powder-Mixed EDM and Cryogenic EDM offer improved efficiency and reduced TW, Automation & AI Integration: Smart EDM systems with AI-driven parameter optimisation can enhance process stability and productivity, New Electrode Materials: The development of wear-resistant electrodes can increase longevity and machining efficiency, Expanding Industrial Applications: Growth in aerospace, biomedical, and electronics sectors drives demand for precision composite machining, Sustainable Machining Solutions: Eco-friendly dielectric fluids and energy-efficient EDM systems can improve sustainability.	Threats Competition from Alternative Technologies: Laser machining and ultrasonic-assisted machining are evolving, offering alternatives to EDM, Material-Specific Challenges: Some composites (e.g., high-fibre PMCs) are complex to machine due to thermal and electrical resistance variations, High Initial Investment: Advanced EDM setups require costly equipment and skilled operators. Regulatory and Environmental Constraints: Stricter environmental laws on waste disposal and energy consumption may impact EDM adoption, Electrode Limitations: Finding optimal electrode materials for various composites remains a challenge for achieving consistent performance.

5. Conclusions

This review study addresses the EDM process, revealing critical insights for optimising this advanced manufacturing process. Focusing on composite materials, investigations worldwide reveal that composites pose significant challenges related to machining costs and TW despite their superior mechanical properties, highlighting the need for innovative machining techniques, such as EDM. The collective research reviewed for this section concludes that while significant strides have been made in machining PMCs, MMCs and CMCs, ongoing innovation in machining techniques is essential. Techniques identical to PMEDM and surface modifications are effective solutions for overcoming conventional challenges in machining PMCs, MMCs, and CMCs; yet, there remains a need for tailored strategies to address the unique properties of each composite material. Future research should continue to investigate parameter optimisation, hybrid machining techniques, and surface modification processes to extend the durability and applicability of PMCs, MMCs and CMCs across demanding applications.

6. Future Research Prospects

Future research should focus on the development and experimental validation of optimised parameters, as well as conducting systematic reviews to establish best practices for the different classes of composite materials. Innovations in EDM technology, combined with a comprehensive analysis of parameters, will be crucial for enhancing machining capabilities and addressing the challenges associated with machining advanced materials.

Furthermore, the development of new materials and processes, supported by academic and industrial sectors, should be accompanied by rigorous experimental planning to minimise waste and reduce final product costs.

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