International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Sinking Electrical Discharge Machining and Wire Electrical Discharge Machining on metal matrix composite: A Review

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Abstract: describes Metal Matrix Composites (MMCs) as advanced materials known for their lightweight, high specific strength, excellent wear resistance, and low thermal expansion. Despite their industrial importance, machining MMCs is challenging due to their hardness and abrasive reinforcement, which causes significant tool wear when using conventional methods. Although nontraditional processes like water jet and laser cutting exist, they are mostly limited to linear cuts. Electrical Discharge Machining (EDM), however, offers superior capability for precise and complex shape cutting of MMCs. The paper reviews the EDM process, summarizes research progress over the years on EDM applied to MMCs, and discusses future research directions in this field.

Keywords: EDM.MMC, WEDM, Process parameters

INTRODUCTION

Electrical Discharge Machining (EDM) is a non-conventional material removal process extensively used for manufacturing dies, punches, molds, and finishing parts in aerospace, automotive, and surgical industries. It is effective for machining electrically conductive materials regardless of their hardness, shape, or toughness. Working Principle of EDM: EDM operates on the principle of thermoelectric energy generated as sparks between a workpiece and an electrode submerged in a dielectric fluid. These two components are separated by a small "spark gap," typically between 10 to 100 micrometers, where pulsed electrical discharges occur through the insulating dielectric medium. The dielectric fluid plays a crucial role by preventing electrolysis effects on the electrodes and helping to maintain the spark gap. The electrode moves toward the workpiece until the gap is sufficiently narrow for the applied voltage to ionize the dielectric fluid, initiating electrical discharges. These discharges erode material from both the electrode and workpiece surfaces without direct contact, thus avoiding mechanical stresses, chatter, and vibration during machining. The process essentially replicates the shape of the electrode onto the workpiece with an offset equal to the spark gap, enabling precise and complex machining.

1.2 Process Parameters

The parameters influencing the EDM process are categorized into electrical and non-electrical parameters.

1.2.1 Electrical Parameters

Key electrical parameters include discharge voltage, peak current, pulse duration, pulse interval, electrode gap, polarity, and pulse waveform.

Discharge Voltage: This is linked to the spark gap and the dielectric fluid's breakdown strength. Before discharge, the open-gap voltage rises with the electrode approaching the workpiece. Once current flows, voltage drops and stabilizes at the working gap level. Higher voltage settings increase the spark gap, improving flushing conditions and stabilizing the machining process.

Peak Current: Peak current represents the power used during each discharge pulse and is the most critical parameter. During each pulse, current rises to a preset peak level, which depends on the surface area being machined. Higher peak currents are employed during roughing operations or when machining large surface areas. Because the machined cavity mirrors the electrode shape, excessive electrode wear caused by high currents can reduce machining accuracy. Advanced electrode materials like graphite are capable of withstanding higher currents with reduced wear

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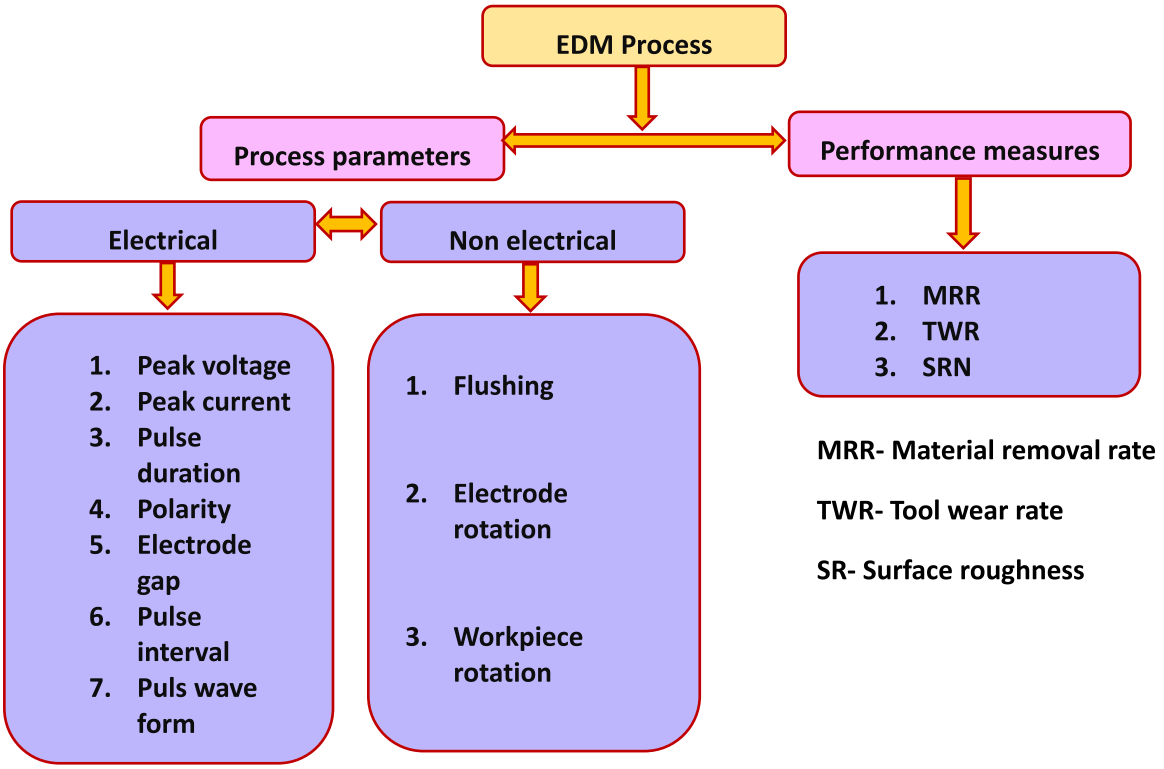

Figure:1: Electrical Discharge Machining Process

Pulse duration, also known as pulse on-time, and pulse interval, referred to as pulse off-time, are typically measured in microseconds. Since material removal occurs only during the pulse duration, this parameter along with the pulse frequency (number of cycles per second) are crucial to the EDM process. The material removal rate (MRR) is directly influenced by the energy delivered during the pulse duration. A longer pulse duration allows more heat to penetrate and dissipate into the workpiece, resulting in a larger recast layer and a deeper heat-affected zone. However, beyond an optimal pulse duration, the MRR tends to decrease, as excessive heat can negatively affect machining efficiency. Pulse interval, or pulse off-time, primarily influences the machining speed and stability of the EDM process. A shorter pulse interval leads to faster machining since the time between sparks is reduced. However, if the interval is too short, the debris from the workpiece may not be effectively flushed away by the dielectric fluid, and the fluid may not fully deionize. This incomplete deionization causes instability in the subsequent spark generation, leading to erratic cycling and extended machining time. Therefore, the pulse interval must be long enough to allow complete deionization of the dielectric fluid, preventing continuous sparking at the same location and ensuring stable machining conditions. The electrode gap in EDM is controlled by a tool servo mechanism, which adjusts based on the average gap voltage. For optimal performance, the system must maintain gap stability and have a fast reaction speed, as any backlash is undesirable. Rapid response is crucial to handle short circuits or open-gap conditions effectively. Electrode polarity, which can be either positive or negative, is typically determined through experimentation. It depends on factors such as the tool and workpiece materials, current density, and pulse duration. Modern EDM power supplies often introduce an opposite polarity "swing pulse" at regular intervals—commonly one swing pulse for every 15 standard pulses—to prevent arcing and improve machining stability. he pulse waveform in EDM is typically rectangular, but generators capable of producing other pulse shapes have been developed. For instance, trapezoidal pulse generators significantly reduce relative tool wear. Some advanced generators also introduce an initial high-voltage, low-current pulse lasting a few microseconds before the main pulse to facilitate ignition. Since EDM is a stochastic thermal process with a complex discharge mechanism, fully explaining the effects of all parameters on performance is challenging. Consequently, researchers often use process analysis techniques to optimize parameters and understand how operating variables influence machining outcomes. Methods like gray relational analysis, as applied by Lin, help address the complex relationships between parameters and multiple

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

performance measures. Additionally, the Taguchi approach is widely employed by researchers for analyzing and designing optimal EDM processes.

1.2.2 Non-Electrical Parameters

The main non-electrical parameters in EDM are the flushing of the dielectric fluid, workpiece rotation, and electrode rotation. These factors play a critical role in optimizing key performance measures such as material removal rate, surface quality, and tool wear.

Research on flushing pressure shows that it significantly impacts surface roughness, tool wear rate, acts as a coolant, and plays a vital role in removing debris from the machining gap. Experimental results by Lonardo and Bruzzone indicate that during roughing operations, flushing pressure affects both material removal rate (MRR) and tool wear rate (TWR), whereas in finishing operations, it primarily influences surface roughness (SR). Both MRR and TWR tend to increase with higher flushing pressure. Additionally, flushing pressure affects crack density and the thickness of the recast layer, which can be minimized by determining an optimal flushing rate through empirical data.

Workpiece rotary motion improves the circulation of the dielectric fluid in the spark gap and temperature distribution of the workpiece yielding better MRR and SR [25]. Similarly, electrode rotation results in better flushing action and sparking efficiency [26]. Hence, improvement in MRR and SR has been reported due to effective gap flushing due to electrode rotation [27–29].

1.3 Performance Measures

The key performance measures in EDM are material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). Research on MRR primarily focuses on understanding the material removal mechanisms and developing methods to enhance MRR. Similarly, studies on tool wear investigate the wear processes and ways to reduce TWR. Although EDM is fundamentally a material removal process, it has also been explored as a surface treatment or additive process, with various surface modifications reported since the technique became widely adopted in manufacturing tool rooms.

1.4 Types of EDM processes

4.1 Sinking EDM

In sinking EDM, the workpiece is shaped either by replicating a specially shaped tool electrode or by three-dimensional (3D) movement of a simple electrode, similar to milling, or through a combination of both methods. The electrode is typically made of copper or graphite. Numerical control systems monitor the gap conditions—such as voltage and current—and synchronously control the movement of different axes along with the pulse generator. The dielectric fluid is continuously filtered to remove debris and decomposition products, ensuring stable machining conditions.

1.4.2 Wire EDM (WEDM)

In Wire EDM, material is removed from the workpiece by a series of discrete electrical sparks generated between the workpiece and a thin copper wire electrode, separated by a continuous flow of dielectric fluid fed into the machining zone. The wire, typically 0.1 to 0.3 mm in diameter, serves as the electrode, while the workpiece is mounted on a CNC-controlled X-Y worktable.

This setup allows the cutting of complex two-dimensional shapes with high precision through controlled movement of the worktable. The wire is continuously fed through the workpiece by a microprocessor, which also maintains the spark gap between 0.025 and 0.05 mm. This process removes the need for elaborate pre-shaped electrodes required in sinking EDM for roughing and finishing operations.

To achieve the desired dimensional accuracy and surface quality, multiple passes of the wire are usually necessary. Wire EDM is widely used not only in tool and die making but also in medical, electronics, and automotive industries due to its ability to machine complex shapes with exceptional accuracy.

1.4.3 Micro-EDM

Micro-EDM is capable of machining extremely small features, including micro-holes and micro-shafts as small as 5 µm in diameter, as well as complex three-dimensional micro-cavities. This capability surpasses that of mechanical drilling, which typically produces holes no smaller than 70 µm, and microfabrication methods like laser machining, which can create holes down to about 40 µm.

Micro-EDM can be categorized into four types:

Micro-wire EDM: Uses a wire with diameters as small as 0.02 mm to cut through the workpiece.

Die-sinking Micro-EDM: Employs electrodes with micro-features to replicate their mirror image onto the workpiece.

Micro-EDM Drilling: Utilizes micro-electrodes with diameters ranging from 5 to 10 µm to drill microholes.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Micro-EDM Milling: Uses micro-electrodes (5–10 µm diameter) to create 3D micro-cavities by following movement strategies similar to conventional milling.

Researchers have developed numerical simulation models for micro-EDM that predict current density, crater area, power dissipation, and channel growth rate. These models' predictions for material removal rate (MRR) per discharge, plasma temperature, and crater radius at the cathode have been experimentally validated and align well with published data.

1.4.4 Powder-Mixed EDM

Powder-mixed EDM differs significantly from conventional EDM. In this process, fine powder particles of a suitable material are added to the dielectric fluid. When voltage is applied, these powder particles disperse within the spark gap, increasing the gap distance between the tool and workpiece from the usual 25–50 µm to about 50–150 µm.

The powder particles cluster and align themselves under the sparking area, forming chains that bridge the gap between the electrodes. This bridging facilitates earlier spark ignition and results in faster sparking during each discharge. Consequently, material erosion from the workpiece surface occurs more rapidly, improving the machining efficiency.

1.4.5 Dry EDM

In dry EDM, the tool electrode is designed as a thin-walled pipe through which high-pressure gas or air is supplied. The gas serves to remove debris from the spark gap and cool the inter-electrode area. This technique was developed to reduce environmental pollution caused by liquid dielectric fluids, which generate vapors during machining and incur costs related to waste management. By using gas instead of liquid dielectric, dry EDM offers a cleaner and potentially more cost-effective machining process.

1.5 Metal Matrix Composite Materials

Metal matrix composites (MMCs) are composite materials composed of at least two distinct constituents. One constituent is a metal, which serves as the matrix, while the other material can be a different metal, a ceramic, or an organic compound that acts as the reinforcement. These composites are produced by dispersing the reinforcing material within the metal matrix to improve mechanical properties.

To enhance compatibility and prevent undesirable chemical reactions between the matrix and the reinforcement, the surface of the reinforcing material can be coated. This coating acts as a barrier that maintains the integrity and performance of the composite.

Metal matrix composites offer significant advantages including high specific stiffness, excellent wear resistance, enhanced strength, weight reduction, high thermal conductivity, low coefficient of thermal expansion, and superior dimensional stability. Due to these exceptional physical and mechanical properties, MMCs have found extensive use in the automotive and aerospace industries. Additionally, these materials exhibit good formability [45, 46].

Typical matrix metals used in MMCs include copper (Cu), iron (Fe), aluminum (Al), magnesium (Mg), titanium (Ti), and lead (Pb). Common reinforcement materials are silicon carbide (SiC), aluminum oxide (Al4O3), and titanium diboride (TiB2). These reinforcements are incorporated in various forms such as whiskers, particulates, or continuous fibers.

Despite their many advantages, the widespread application of MMCs is limited by challenges during secondary conventional machining processes like turning, drilling, and milling. These challenges arise primarily from poor machinability, reduced productivity, and compromised quality of the machined product. Machining MMCs often results in high tool wear rates, sub-surface damage, and cracking [47– 49].

Alternative machining methods such as water jet and laser cutting can be employed, but they are generally limited to linear cutting operations. Electrical Discharge Machining (EDM) is more effective for MMCs, enabling the cutting of complex shapes with high precision [48, 50]. Today, EDM is widely used for machining a variety of materials, including high alloy tool steels, conductive ceramics, germanium, alumina substrates, and polycrystalline diamonds, achieving accuracy and surface finishes down to the submicron range [47, 51–56].

Let me know if you need this text summarized, expanded, or adapted for a specific use.

2. RESEARCH IN SINKING EDM ON METAL MATRIX COMPOSITES

2.1 SiC/Aluminum Matrix

Ramulu and Taya investigated the machinability of SiC whisker-reinforced 2124 aluminum matrix composites (SiCw/Al) with volume fractions of 15% and 25% SiC [57]. The samples were machined under coarse, medium, and fine conditions using copper and brass electrodes. Their study found that the material removal rate (MRR) increased with the power applied to the electrode.

Comparatively, the MRR for the 15 vol.% SiCw/2124 Al composite was higher than that for the 25 vol.% SiCw/2124 Al composite. When using a copper electrode, the MRR

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

was observed to be 5–10% lower than that achieved with a brass electrode. Additionally, machining time was longer for the 25 vol.% SiCw/Al composite compared to the 15 vol.% composite.

Micro-hardness tests on the SiCw/Al composites revealed that machining at slower cutting speeds caused surface softening. Conversely, higher cutting speeds led to micro-damage in both the surface and sub-surface regions.

Let me know if you want me to continue or elaborate on this topic.The provided text is a comprehensive literature review on electrical discharge machining (EDM) of particle-reinforced aluminum matrix composites, particularly those reinforced with silicon carbide particles (SiCp/Al). Here is a concise summary highlighting key points and findings from the studies mentioned:

Hung et al. (1994):

Investigated EDM on cast aluminum MMC reinforced with SiC particles.Found that SiC particles reduce metal removal rate (MRR) by shielding aluminum from vaporization.Formation of a re-cast layer (RCL) occurs from unmeltedSiC particles and molten aluminum.MRR and RCL depth are mainly controlled by input power; current dominates surface finish.No cracks were found in the re-cast layer or heat-affected zone.

De Silva and Rankine:

Observed melting of aluminum matrix and dislodgement of SiC particles during EDM. SiC particles flushed away by dielectric fluid.

Hocheng et al.:

Applied heat conduction models to correlate machining parameters (current, pulse duration) with crater size and MRR.Found crater size larger for SiC/Al than steel.Recommended large current and short ontime for effective machining.

Karthikeyan et al. (1997):

Developed mathematical models for EDM of Al-SiC composites.MRR increases with current, decreases with SiC volume and pulse duration.Tool wear rate (TWR) increases with current and SiC volume; surface roughness (SR) increases with all three parameters.Optimized parameters to maximize MRR and minimize TWR and SR.

Muller and Monaghan:

Compared EDM, laser cutting, and abrasive water jet machining on SiC/Al composites.Found EDM suitable but slow; machining results in crater-like surface with minor subsurface damage.

Ramulu et al.:

Studied effect of EDM surface roughness on fatigue behavior of 15 vol.% SiCp/A336 composite.Found surface damage from recast layer and pitting reduces fatigue strength by 15-20%.

Mohan et al.:

Studied effects of electrode material, polarity, current, pulse duration, and SiC volume on EDM of AlSiC composites.Positive polarity, higher current, and brass electrodes improved MRR.Increased SiC volume and pulse duration decreased MRR.Surface roughness increased with SiC volume and current.

P. Narender Singh et al.:

Used gray relational analysis for multi-response optimization of EDM parameters on Al-10%SiCp composites.Investigated effects of current, pulse on-time, and flushing pressure on MRR, TWR, taper, radial overcut, and SR.Higher current and pulse on-time increased MRR but reduced dimensional accuracy.

Mohan et al. (rotary EDM study): Studied rotary EDM with tube electrodes on SiC/6025 Al composites.Found tube electrode drilling yields higher MRR than solid electrodes.Smaller electrode hole diameter improves surface quality and MRR but increases electrode wear.Increased SiC volume decreases MRR and SR, increases electrode wear.

Seo et al. (2006):

Investigated machining of functionally graded SiCp/Al composites.Found MRR increases with SiC percentage and optimized current/pulse on-time.Higher energy conditions produce rougher surfaces with recast material patches and cracks.Developed response surface models correlating parameters and machining outcomes. **Sushant Dhar et al.:**

Modeled machining of cast Al–4Cu–6Si alloy–10 wt.% SiCp composites.Found MRR, TWR, and radial overcut increase nonlinearly with current.Pulse duration increases MRR and radial overcut; gap voltage has minor effect.Potential industrial application in automotive sector.

Akshay Dvivedi et al.:

Studied EDM machinability of Al6063 SiCp composite developed by melt stir-squeeze-quench casting.Identified optimal parameters for maximum MRR with acceptable TWR and dimensional accuracy.Pulse current is the most significant factor influencing MRR.Emphasized importance of flushing pressure and gap control.

General Observations:

SiC reinforcement generally reduces MRR due to shielding effects.Process parameters such as current, pulse duration,

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

electrode material, and flushing conditions significantly affect MRR, TWR, and surface quality.Mathematical and statistical modeling, including gray relational analysis and heat conduction models, are widely used for parameter optimization and prediction.Surface integrity and mechanical properties (e.g., fatigue strength) are adversely affected by EDM-induced thermal damage and recast layers.Rotary EDM and electrode design improvements enhance machining efficiency.Optimal machining involves

2.2Al2O3/Aluminum Matrix

Yan and Wang:

Investigated EDM drilling of Al2O3/6061Al composite using rotary EDM with a hollow tube electrode. Found EDM drilling feasible and preferable over other machining methods like water jet, laser, and wire EDM for complex shapes. Hollow tube electrodes yield higher material removal rate (MRR) than solid electrodes, despite higher tool wear rate (TWR).Peak current and volume fraction of Al2O3 strongly affect MRR, TWR, and surface roughness (SR), while electrode rotation speed and flushing pressure have minor effects. Optimized flushing pressure and electrode rotation maintain a constant cutting feed rate. Developed empirical models to predict performance measures. Introduced innovative features: electrode rotation and hollow tube electrode design, opening new research directions in EDM of metal matrix composites (MMCs).

Che Chung Wang and Biing Hwa Yan:

Studied optimization of blind-hole drilling of Al2O3/6061Al composite using rotary EDM with an eccentric through-hole electrode. Used Taguchi methodology for experimental design. Found blindhole drilling feasible with higher MRR and electrode wear using rotational eccentric through-hole electrode. Electrical parameters have a stronger influence on machining than non-electrical parameters.

Electrode polarity significantly affects MRR and surface roughness; peak current mainly influences electrode wear. Increased electrode rotational speed, dielectric fluid pressure, and dual eccentric holes can enhance MRR within limits. Developed semi-empirical models for MRR, TWR, and SR prediction. Highlighted the new electrode design and the role of electrode rotation in performance.

2.3 Powder-Mixed EDM

Kansal et al.:

Conducted experimental study on machining Al-10%SiCp composites using powder-mixed EDM. Mixed aluminum powder into the dielectric fluid with a modified circulation system. Used response surface methodology to study effects of powder concentration, peak current, and pulse duration

balancing process parameters to maximize MRR while minimizing tool wear and surface defects.If you need a more specific summary, analysis, or help with a particular section, please let me know

The provided text covers studies on machining characteristics of aluminum matrix composites with alumina (Al2O3) reinforcement and the use of powder-mixed EDM techniques. Here's a summary of key insights:

on machining rate and surface roughness. Identified important parameters and optimized conditions for maximum machining rate and minimum surface roughness. Verified optimal conditions through confirmation experiments. Results can be compared with conventional sinking EDM to evaluate powder-mixed dielectric effectiveness.

Singh et al. (2008):

Compared machinability of stir-cast 6061Al/Al2O3P/20p composites using plain dielectric and silicon carbide abrasive powder-suspended dielectric. Used copper electrode and evaluated surface roughness. Applied Lenth's method to identify significant parameters and optimize machining settings. Found abrasive particle size, particle concentration, and pulse current to be most significant for surface quality. Focused on surface roughness as the primary performance measure. Provided comparative insight into the benefits of powder-mixed EDM versus traditional EDM.

The section on "Other MMCs" discusses a recent study by Ahamed et al. on hybrid metal matrix composites (MMCs), which incorporate two or more types of particulate reinforcements. Here is a summary of the key points:

Material Studied: Hybrid MMCs of aluminum reinforced with 5% SiC combined with either 5% B4C or 5% glass particles, prepared by stir casting.

Objective: To investigate the effect of machining parameters—current, pulse on-time, pulse off-time, and flushing pressure—on material removal rate (MRR) and surface roughness (SR) during EDM.

Findings:

The ceramic reinforcements (SiC, B4C, glass) impede the machining process. A trade-off exists between machining parameters to maximize MRR while minimizing SR. Longer spark duration is required to effectively remove hard particles like SiC and B4C embedded in the matrix. Glass particles, having lower density than B4C, are more easily flushed away at relatively lower flushing pressures. A prominent white (recast) layer forms on the machined surfaces of both composites.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Research Focus and Gaps:

The study focuses on the influence of EDM parameters on MRR and surface roughness. Electrode wear has not been addressed, indicating room for further investigation. The work suggests significant potential for future research on EDM of hybrid MMCs with multiple particulate reinforcements.

This research contributes to understanding the machining challenges and behavior of hybrid MMCs and underscores the complexity introduced by multiple reinforcements during EDM. If you would like, I can assist in elaborating on potential research directions or comparing these findings with other MMC studies.

3.RESEARCH IN WIRE EDM ON METAL MATRIX COMPOSITES

Wire electrical discharge machining (WEDM) is recognized as an effective and cost-efficient method for machining modern composite materials, including metal matrix composites (MMCs). However, research on applying WEDM specifically to MMCs remains limited. In a notable study, Gatto and Iuliano conducted WEDM experiments on two types of SiCreinforced 2009 aluminum alloy composites: one containing 15% whisker reinforcement and the other with 20% particle reinforcement. They performed tests under one roughing condition and two finishing conditions. To understand the machining effects on both the reinforcement and the aluminum matrix, they analyzed the machined surfaces, cross-sectional profiles, and microstructures using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). This approach helped reveal the behavior of the composite materials during WEDM, including how reinforcements and matrix material respond to the process.

The paper places special emphasis on the surface quality of machined composites, particularly examining the effects of different reinforcement types—particle versus whisker—on the machined surface. An additional important aspect of the study is the investigation of glass bead peening as a post-processing technique to improve the machined surface.

In related work, Rozenek et al. conducted experimental investigations to assess how machining parameters—discharge current, pulse on-time, pulse off-time, and voltage—affect machining feed rate and surface roughness when machining metal matrix composites AlSi7Mg/SiC and AlSi7Mg/Al2O3. Their key findings include:

Both feed rate and surface roughness increase with higher discharge energy. At a pulse-on time of 1.6 µs, pulse-off time of 8 µs, and 80 V gap voltage, increasing discharge current raises the feed rate and surface roughness parameter Ra. Decreasing voltage gradually reduces both feed rate and surface roughness. Longer pulse-on times lead to higher feed rates and roughness. The maximum cutting speeds for AlSi7Mg/SiC and AlSi7Mg/Al2O3 composites are roughly 3 times and 6.5 times slower, respectively, than for pure aluminum alloy. This research highlights the significant impact of reinforcement type on machining performance, though it does not address how varying the volume fraction of reinforcement influences these outcomes. Rozenek et al. conducted an experimental study to examine how machining parameters—discharge current, pulse on-time, pulse off-time, and voltage—affect feed rate and surface roughness during the machining of metal matrix composites AlSi7Mg/SiC and AlSi7Mg/Al2O3.

Key findings include:

Both feed rate and surface roughness increase as discharge energy increases. At specific settings (1.6 µs pulse-on time, 8 µs pulse-off time, and 80 V gap voltage), increasing current raises both feed rate and surface roughness (Ra). Decreasing voltage causes a gradual reduction in feed rate and surface roughness. Longer pulse-on times lead to higher feed rates and roughness values. The maximum cutting speeds for AlSi7Mg/SiC and AlSi7Mg/Al2O3 composites are about three times and 6.5 times slower, respectively, compared to pure aluminum alloy. This study highlights the significant impact of machining parameters and reinforcement type on machining performance and surface quality of MMCs. The machining rate of metal matrix composites (MMCs) is significantly influenced by the type of reinforcement material used. This makes the investigation into how different reinforcements affect machining performance especially important. However, the effect of the reinforcement's volume percentage on machining performance remains unpredictable based on the current research.

Guo et al. studied the machining of 6061 aluminum alloy reinforced with 20% Al2O3 particles using wire electrical discharge machining (WEDM) at high travel speeds.

Their key findings include:

Electrical parameters had little impact on the surface roughness, which remained coarse regardless of whether high or low energy settings were used. Electrical parameters significantly affected the cutting rate. Low energy settings, especially combined with low pulse duration and low machining voltage, caused wire breakage due to blind feeding. High pulse duration, high voltage, large machining current, and an appropriate pulse interval collectively enabled high machining efficiency. This study emphasizes the importance of selecting suitable electrical parameters to

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

optimize cutting efficiency and minimize issues like wire breakage when machining particle-reinforced composites. This research focuses on comparative experiments using wire electrical discharge machining (WEDM) to shape metal matrix composites (MMCs), specifically optimizing electrical parameters to improve machining performance.

Yan et al. [82]:

Investigated WEDM of 6061 aluminum alloy and composites reinforced with 10% and 20% volume fraction of Al2O3 particles. Varied pulse on-time to study its effect on cutting speed, slit width, and surface roughness. Found cutting speed highest for pure 6061Al, with the two composites showing similar but lower speeds. Increasing Al2O3 volume fraction led to more frequent wire breakage due to abrasive particle effects. Machining 6061Al and 10% Al2O3 composite resulted in smoother surfaces than the 20% Al2O3 composite. The 20% Al2O3 composite produced a much narrower slit width. Protruding Al2O3 particles in the discharge gap caused the brass wire to shift, creating visible banding on the machined surface, especially under low wire tension. Higher reinforcement content deepened and widened wire surface craters,promoting wire breakage. Wire breakage was attributed to softening of the brass wire from high temperatures during machining, which reduced its tensile strength.To minimize wire breakage, very low wire tension, high flushing rate, and high wire speed are recommended. Appropriate servo voltage, short pulse-on and pulse-off times (which correlate with high cutting speed) had little effect on surface roughness for composites. This study importantly analyzes wire breakage mechanisms, guiding future development of wire electrodes with improved high-temperature creep resistance to reduce breakage.

Patil and Brahmankar [83]:

Studied WEDM performance on Al/SiCp composites, analyzing pulse on/off time, ignition current, wire speed, tension, and flushing pressure on cutting speed and surface finish. Used Taguchi design for experiments and developed mathematical models relating machining parameters to performance. Found unreinforced aluminum alloy had higher cutting speeds than composites, but composites showed better surface finish. Wire breakage limited the cutting speed achievable for composites. The work contributes parameter optimization and theoretical modeling for machining MMCs via WEDM.

Manna and Bhattacharyya conducted an experimental investigation to determine optimal parameter settings for machining aluminum-reinforced silicon carbide metal matrix composites (Al/SiC-MMC) using CNC wire-cut EDM.

Key findings from their study include:

Open-gap voltage emerged as the most significant parameter influencing the material removal rate (MRR) and cutting speed. Pulse-on period was identified as the second most important factor affecting MRR. Wire tension and wire feed rate were the primary parameters influencing surface roughness, with wire tension having the most significant effect. For controlling the spark gap, wire tension and spark gap voltage were the most influential parameters. Open-gap voltage and gap current were found to be the most significant parameters affecting the gap current. The researchers developed mathematical models based on the experimental data to describe the relationships between machining parameters and performance measures. Verification tests confirmed the accuracy of these models. The results were used to select an optimal combination of machining parameters for effective and efficient machining of Al/SiCMMC. This study contributes both practical insights for parameter optimization and theoretical modeling to better understand and control the wire-cut EDM process for Al/SiC composites.

Saha et al. (2009) investigated the machinability of a 5 vol.% TiC/Fe in situ metal matrix composite using wire electrical discharge machining (WEDM). The study focused on understanding the effects of key input parameters—pulse on-time, pulse off-time, wire feed rate, and average gap voltage—on performance measures including cutting speed and kerf width.

Key points from their research:

The presence of TiC particles and the formation of Fe2O3 during machining caused process instability, making modeling challenging. The authors modeled the WEDM process using a normalized radial basis function network (NRBFN) combined with an enhanced k-means clustering technique. Both the experimental data and model predictions were used to carry out a parametric study and to assess the model's effectiveness. Results showed that increasing the average gap voltage decreased cutting speed but increased kerf width within the studied range. Pulse on-time had a lesser effect on cutting speed and kerf width compared to the average gap voltage. However, increasing pulse on-time increased both cutting speed and kerf width. Among various network configurations tested, a 4–21–2 architecture provided the best prediction accuracy. This study highlights the complexity of machining TiC/Fe composites and demonstrates the effectiveness of advanced neural network modeling for capturing the nonlinear relationships between machining parameters and performance outcomes.

The research on the TiC/Fe composite is notable as it explores a relatively new material using the normalized radial basis function network (NRBFN) technique. This modeling approach offers several advantages, including lower complexity, fewer required training samples, straightforward input-output mapping, and a reduced risk of getting trapped in local minima during training, making it well-suited for studies of this nature. In 2009, Liu et al. studied wire electrochemical discharge machining (WECDM) of Al_2O_3 particle-reinforced 6061 aluminum alloy. They evaluated how machining voltage, current, pulse duration, and electrolyte concentration influence the material removal rate (MRR), considering the combined effects of wire electrical discharge machining (WEDM) and electrochemical machining (ECM) in the process.

Key findings include:

High current and high electrolyte concentration enhance ECM activity, leading to increased MRR. Orthogonal analysis revealed that among the parameters studied, applied current has the greatest influence on MRR, followed by pulse duration and electrolyte concentration. The results were supported by experiments and explained through factors such as the matrix phase surface area and spark gap size. The study compared two machining processes—WEDM and ECM—applied to the same material, with MRR as the sole performance measure considered. This work provides valuable insights into the interplay between electrical discharge and electrochemical processes in machining particle-reinforced aluminum alloys and highlights the critical role of current in optimizing material removal.

4. DISCUSSION AND FUTURE TRENDS

After a thorough review of the published literature, the following conclusions can be drawn:

The majority of research on machining metal matrix composites (MMCs) has focused on the sinking EDM process, with relatively little work reported on wire EDM. Most studies concentrate on SiC-reinforced MMCs, whereas fewer investigations have been conducted on Al_2O_3-reinforced and other types of MMCs. Several promising MMC materials have yet to be explored as work materials in EDM processes. Table 1 (referenced) lists some MMCs along with their applications that remain untested in EDM. Research on powder-mixed EDM of MMCs is limited, primarily involving aluminum and SiC powders. Other promising powders such as boron carbide and powders of alloying elements like manganese, chromium, molybdenum, and vanadium have yet to be investigated as additives in the dielectric fluid.

Table 1 Some important MMCs yet to be tried on EDM

S.NO.	MMC system	Industrial application
1.	Cobalt matrix with hard tungsten carbide particles	Carbide drills
2.	Steel reinforced with boron nitride	Tank armors
3.	Aluminum boron carbide matrix	Driveshaft
4.	Monofilament silicon carbide fibers in a titanium matrix	F-16 fighting falcon(jet’s landing gear)
5.	Al_2O_3 -SiO_2 /AC4C	Vane, Pressure side plate of oil pressure vane pump
6.	SiCw/7075	Joint of aerospace structure

Most research efforts have been directed toward optimizing process parameters to improve performance measures. These studies mainly focus on electrical parameters and flushing pressure as a non-electrical parameter. There is very limited work on the effects of other nonelectrical parameters such as workpiece rotation and electrode rotation. Only one study has addressed changes in mechanical properties of EDM-processed MMCs, indicating that this area remains largely unexplored and offers significant scope for future research. Overall, these gaps highlight opportunities for expanding

the scope of EDM research on MMCs, including exploring diverse materials, advanced powder-mixed techniques, non-electrical parameter effects, and the impact on mechanical properties. Many metal matrix composites (MMCs) remain unexplored regarding the selection of suitable electrode materials and electrode designs, as research in these areas is

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

currently very limited. There is a lack of comprehensive theoretical models for simulating the relationships between input parameters and output responses during EDM of MMCs. This area requires significant future research efforts. Emerging EDM techniques, such as dry EDM and EDM using pure water as the dielectric fluid, represent promising future directions. MMCs have yet to be investigated extensively within these novel machining approaches.

5. SUMMARY

This paper presents a comprehensive review of research conducted over the past 20 years on machining metal matrix composites (MMCs) using sinking EDM, wire EDM (WEDM), and powder-mixed EDM. Despite the different methods employed, the overarching objectives remain consistent across all studies: to improve machining performance, achieve higher quality finished products, and create better working conditions during the EDM process.

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