

Machinability of Metal Matrix Composites Using Wire Electric Discharge Machining: A Review

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Abstract

Metal Matrix composites [MMCs] are increasingly being applied in the automotive and aerospace industries as high-performance substitutes for traditional materials. Due to these properties, namely, high strength-to-weight ratio, outstanding fracture toughness, and low density, a vast array of uses is feasible. We can control the properties of MMCs directionally as well, which makes them the perfect choice for military uses and marine and sports equipment. The machining of MMCs plays a crucial role in producing various parts and components. Although conventional machining of metals and alloys is widely practised in aerospace, biomedical, and automotive applications, MMCs are different due to the properties of metal matrix and reinforced materials. However, there are issues with the conventional way of processing, namely hardening, tool wear, thermal stresses and inconsistent surface roughness. In this article, the author focuses on the topic of machining of MMCs Wire Electric discharge machining, a popular variant of electric discharge machining methods. It starts with the description of MMCs, the reasoning for their application, and the challenges in the machining process. It then discusses previous studies on the machining of MMCs using advanced methods of wire electrical discharge machining. The article also covers productivity and surface integrity problems like delamination and surface roughness while looking at the opportunities and threats of these new-age processes.

Keywords: WEDM, metal matrix composite, surface integrity, material removal, alloys.

INTRODUCTION

Metal Matrix Composite- An Overview

Metal matrix composites [MMCs] are advanced materials with metallic matrixes containing ceramic or other metal reinforcements like substances. MMCs mainly consist of two major constituents: Matrix and Reinforcement. The matrix is primarily made of light material, mostly metals such as aluminium, magnesium, or titanium. Among these materials, aluminium-based matrix composites [AMMCs] are particularly prevalent due to their favourable strength-to-weight ratio and corrosion resistance[1]. The second material is known as reinforcement and is usually made of ceramics such as silicon carbide [SiC], alumina [Al₂O₃], and titanium carbide [TiC]. These reinforcements can be in the form of continuous fibres, short fibres or particles, which greatly influence the mechanical properties of the composite. Some recent studies have also shown that MMCs have High Strength & Stiffness. MMCs exhibit superior mechanical properties to traditional metallic materials, making them suitable for demanding applications across diverse industries[2]. They are further helpful in high-friction applications because hard ceramics reinforcements offer increased wear resistance in the case of MMCs. MMCs can work for aerospace and automotive applications, as they can retain their mechanical properties even at high

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temperatures[3]. Their adaptability in selecting matrix and reinforcement materials allows users to tailor MMCs' properties per specific applications, leading to materials design innovations[4]. Figure 1 depicts the primarily various options for matrix and reinforcement material used for the fabrication of metal matrix-based composites.

Selection and Manufacturing Techniques

The matrix part of a material is crucial for load distribution and reinforcement so that the material can withstand load without failure. The structural integrity of the MMCs is also retained by it. Usually, it is a light material with low density, due to which Al, Mg, and Ti are used as matrix materials; among these, Al has lately been focused on as matrix material[5]. In MMCs, the second most essential part consists of reinforcement materials that determine the properties and performance. Reinforcement in MMCs mainly involves improving mechanical properties like strength since a significant amount of load is carried through reinforcement materials, thereby increasing the strength as well as stiffness of MMCs. For instance, reinforcement materials can be chosen to make the metal harder so that it can be used for sliding or abrasion applications due to its anti-wear properties [6]. It also facilitates customisation or improvisation of properties such as thermal and electrical properties and density control, making them suitable for aerospace & automotive components. To develop specific material properties for a given application, selecting the right type, size, and volume fraction of reinforcement are important aspects when designing MMCs. The composite materials' overall performance is significantly influenced by the interface between the reinforcement matrix [7]. Different methods can be employed in manufacturing Metal Matrix composites [MMCs] including liquid state processes, solid-state processes and advanced techniques. Below figure 2 briefly shows a classification on manufacturing of MMCs[8].

APPLICATIONS OF METAL MATRIX COMPOSITES

The versatility and superior properties of Metal Matrix composites [MMCs] make them suitable for a wide range of applications in various industries, including aerospace, automotive, defence, electronics, sports equipment, medical tools and energy[7]. It is expected to drive the adoption of MMCs up as manufacturing methods become more advanced and costs decline, which will lead to further advancements and novel applications in the future. Lightweight nature, superior mechanical properties, and adaptability are among the reasons why MMCs are increasingly used in different industries[9]. The following applications are some examples from recent

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Aircraft structures, engine components and thermal protection systems; the Automotive sector where pistons or connecting rods or brake parts or cylinder liners make use of MMCs; Military applications like missile structures or high-speed mechanical systems which take advantage of MMCs; High-performance sporting goods such as golf clubs/ tennis racquets/ fishing rods consist of MMCs; An example is that these composites have light weights and they have high strengths so they improve performance and durability of sports equipment- Implants/prosthetics where there's a fast-growing application for MMCs[10][11].

Aluminium-based MMCs find applications in various industries, e.g. Space. Because of their strength-to-weight ratio and thermal stability, it is used in aircraft components and structures[12].

Automotive

These composites are used in engine components, braking systems and construction materials to increase performance and reduce weight. Industrial Tools: Resistance to corrosion makes it suitable for cutting tools and dies[13][Figure.3].

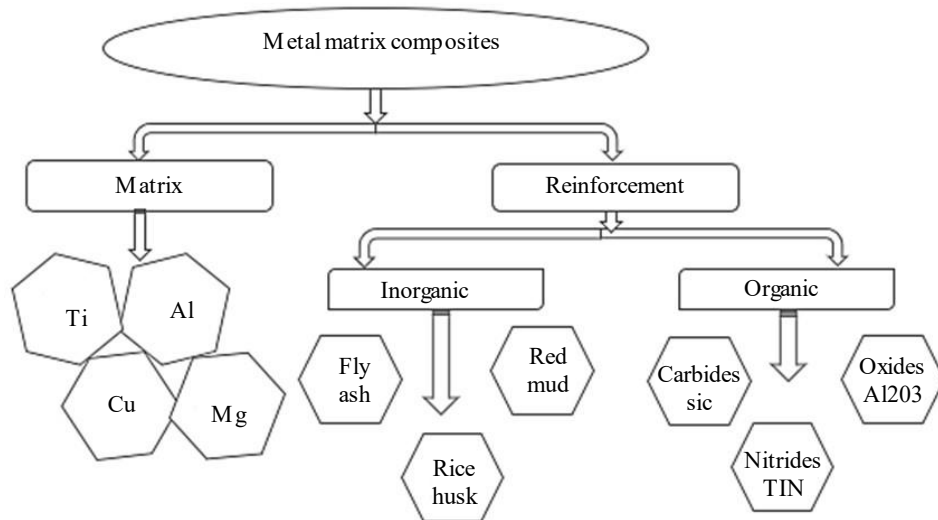


Figure 1. Various materials used for metal metrix composites.

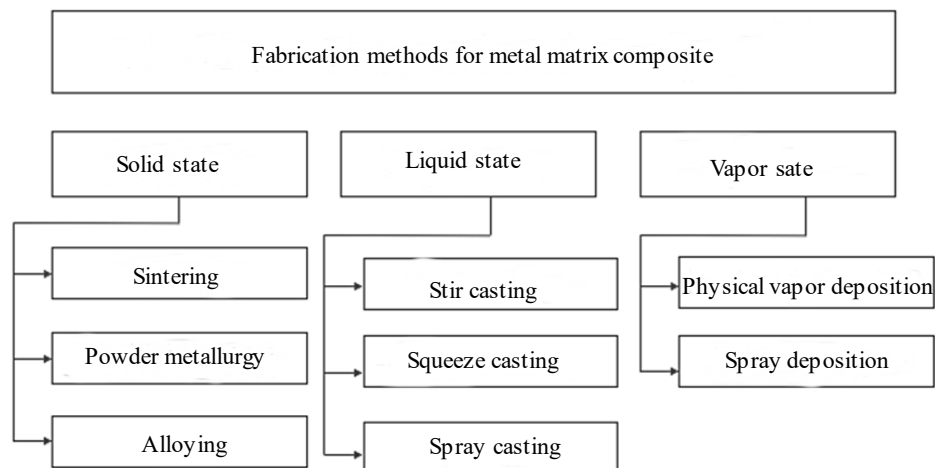


Figure 2. Fabrication Methods for MMCs.

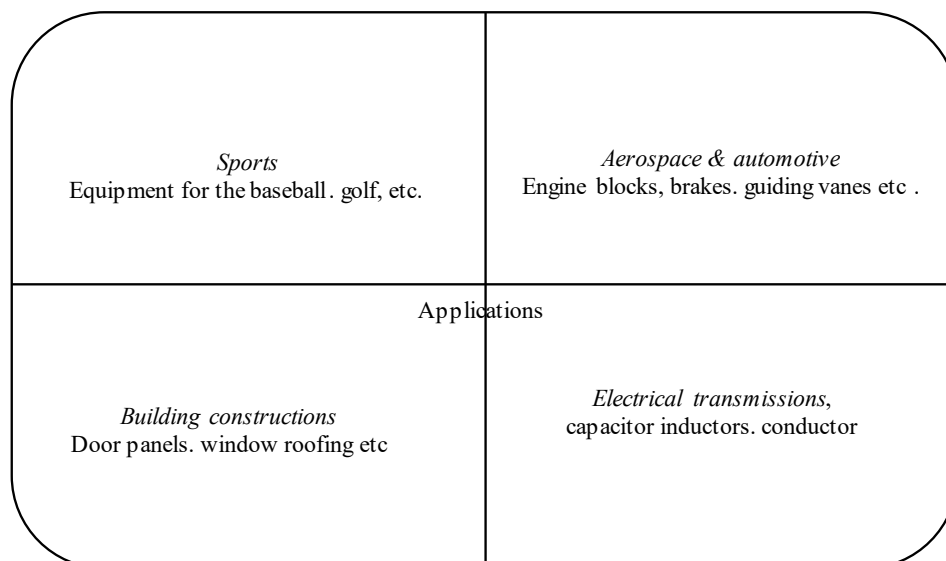


Figure 3. Applications of MMCs.

MACHINING CHALLENGES FOR MMCS

Cutting and shaping MMCs plays a crucial role in turning advanced materials into working parts. This process tackles problems, boosts sustainability, and opens doors for new uses across many fields. Cutting Metal Matrix composites [MMCs] brings up many issues because of the rigid particles mixed in [14]. Here are some significant issues: Hard bits like silicon carbide [SiC] and alumina [Al₂O₃] wear down cutting tools fast. This makes tools last less time and costs more money. The harsh particles can scratch and groove the metal, leaving rough surfaces [15]. It's hard to get a smooth finish when cutting MMCs. You need more force to cut through MMCs because of the hard bits inside. This uses more power, can bend tools, and causes shaking, which hurts the finish and size accuracy. MMCs tend to build up material on the cutting edge of tools. This can make chips form and leave a rough surface. When you cut MMCs, the chips break into small pieces because the hard particles crack. This can make it tough to clear away chips and might damage the cut surface [16]. The metal and the hard bits inside expand at different rates when heated. This can leave stress in the material after cutting [17].

REVIEW OF PREVIOUS STUDIES ON EDM OF MMCS

Electrical discharge machining [EDM] is one of the non-traditional machining processes in which the material is removed by electrical discharge between the workpiece and tool. It is very advantageous for machining hard and electrically conductive materials like metal matrix composites. M.M.C.s EDM operates by creating a series of sparks and creating a gap between an electrode and the workpiece, which is submerged in a dielectric fluid. The discharge of electrical energy makes small portions of the material of the workpiece melt and vaporise; hence, sculpting is made accurate. Conventional EDM technology employs a custom-made electrode to cunningly manufacture precise shapes and geometries. Wire Electrical Discharge Machining [WEDM] is another type of electrical discharge machining process in which a fine wire is used as the electrode tool. EDM is widely used in various industries, including aerospace, automotive, and tool-making industries, to make moulds, dies, and other complex parts that require high levels of precision. Affordable accuracy and detailed shapes in artistic creation. Reduced mechanical strain: Some materials are very sensitive and may be affected by mechanical pressure during the procedure; non-contact element reduces such deformities. Figure 4 depicts the schematic diagram for WEDM [18]. While machining MMCs using WEDM, various factors namely type of metal used as matrix as different materials are having different thermal and electrical conductivity [19], reinforcement material type and size of material also play a critical role while machining using WEDM [20]. Fractional volume of reinforce material also effect the machinability with WEDM as it increases chances of wire breakage goes up [21] and surface finish of machined material deteriorate.

Lodhi et al. [22] worked on an Al-based composite using RSM methodology utilising Box Beckham using spark timing, peak current and wire feed as input parameters to optimise MRR and find the role of these factors in the surface integrity aspect of the machined surface. They gave insight for machining this composite using WEDM, they also present surface integrity aspect of machined surface for the material. Multi-optimisation was performed using the desirability approach. Soutrik Bose & Titas Nandi [23] worked on a Titanium metal matrix composite and developed a relation for MRR, Sr and Kerf width with power, peak current and spark-off timings. They further utilised multi-optimised GA with a desirability approach for multi-optimising the response factors.

Nilesh kumar et al. [21] worked on hybrid composite Al 6061, SiC, and TiB₂ using WEDM; they found peak current and spark timing significantly affect surface roughness and recast layer thickness. They proposed a trim-cut method to reduce the recast layer and surface roughness during processing [Figure 5]

The above depicts the material fabricated and recast layer thickness after processing using WEDM. As energy increases, recast layer layers increase and vice versa.

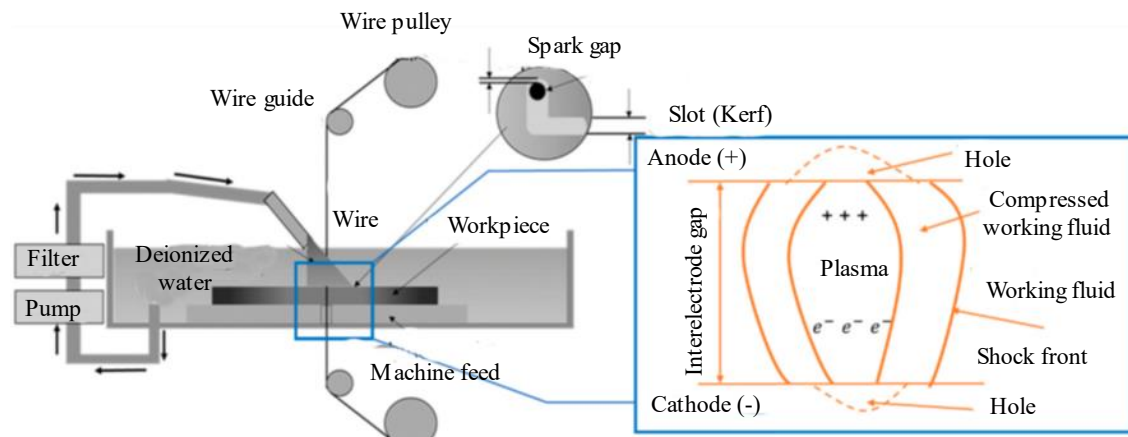


Figure 4. Working Diagram of WEDM [6].

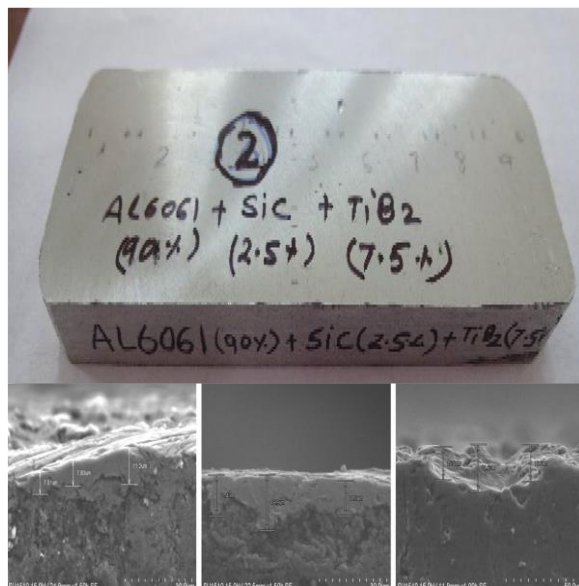


Figure 5. Fabricated MMC & Recast Layer after processing using WEDM [7].

Khanna et al.[24] worked on an Al-based hybrid composite using a combined method of adaptive RSM & TLBO approach to optimise the kerf width while processing on WEDM; they found an improvement of 18.24% in Cutting speed and a reduction of 17.11% in kerf width. Pallabika Sarmah et al.[25] worked on Al/SiC-based MMCs with two grit-sized samples, 200 & 600, then tried to conclude the machinability aspect for both composites using WEDM. They found that the I_p factor was most significant for machining time, whereas for Kerf width, the T_{on} factor was the most important while machining both composites. Gore et al. [26] worked on Al/SiC/p material on WEDM to predict crater size and MRR based on the particle size used. They utilised FEM analysis on MATLAB and found a relation between crater size and SiC volume in the composite.

Ansari et al. [27] worked on AMCs material to fabricate a microchannel using WEDM, as shown in Figure 6. They have studied the effect of input parameters on MRR, TWR and surface roughness. Performed single and multiple optimisations using Taguchi and GRA approach. G Ramanan et al.[28] worked on Aluminium 7075 and carbon-activated reinforcement using the WEDM process, they concluded the usefulness of WEDM in processing the material. They developed empirical relations for material removal rate and surface roughness with various input factors. Research on Ti-B4C nanocomposites shows that high pulse-ON time increases the surface roughness resulting from excessive melting, whereas high pulse-OFF times lead to reduced MRR and improved surface

quality[29]. For Mg-HNT-Zr composites, it is observed that a Taguchi-coupled grey relational analysis revealed improved parameters for minimum surface roughness and maximum MRR, including higher pulse-ON times and lower pulse-OFF times [30][Figure.7]

It was found during a literature survey that most the metal matrix composite sparks on time and peak current played a vital role during machining, as discussed above; in the same line, other groups of researchers were S Vinoth et al. [31] for AA6070/MgO, S. Pratap Singh et al. Al6061-10 %Al₂O₃ [32], Z Seikh et al. for Al-RHA [Rice Husk Ash][33]. One of the challenges during processing composite using WEDM remains an issue of wire tool breakage; some of the authors tried to address the challenge. For instance, Shireesha et al. [34] focussed on optimising the input factor while eliminating wire breakage possibilities and enhancing the overall effectiveness of the process.

Literature survey indicates and confirms the applicability of WEDM for the fabrication of components for composite material. Most of the researchers report that peak current and spark on time are the most significant factors while processing using WEDM. MRR and Surface roughness are two objective remains on either side of combinations of input factors so a trade-off occurs between these two objectives while machining composite using WEDM. However, these issues addressed by multi-optimisation methodology to improve the overall effectivity of process to fabricate component for metal matrix composite.

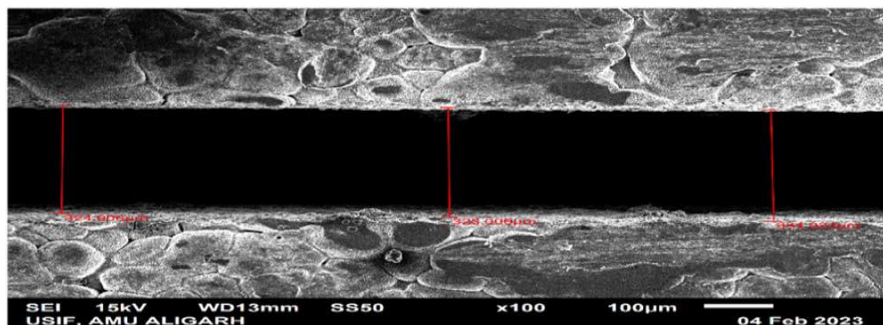


Figure 6. SEM image for channel created in MMC using WEDM [13].

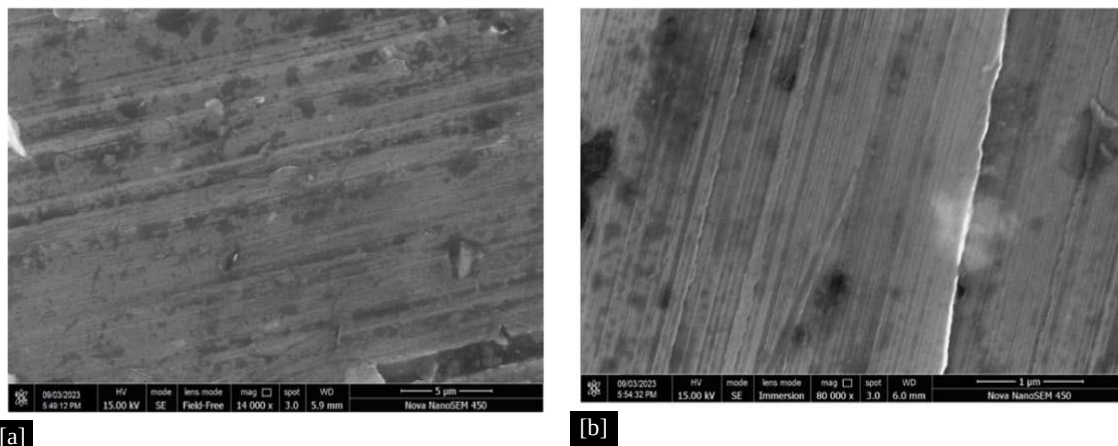


Figure 7. SEM image for machined Al-based composite at optimum condition using WEDM [14].

CONCLUSION & FUTURE DIRECTIONS

This paper gives an overview of the new developments in the machining of Metal Matrix composites [MMCs] with the latest advances in the field. Some of the unique characteristics of MMCs comprises of high strength-to-weight ratio, thermal conductivity, stability in dimension, low specific gravity, coefficient of thermal expansion and higher specific stiffness; MMCs have certain advantageous features that make them suitable for railroad, aerospace, automobile, biomedical and marine

applications. Current research and development in the technology of machining is focusing on several factors that are related to MMCs. Therefore, it can be concluded that while some progress has been made regarding the accuracy of MMC machining, the necessary mechanical properties of these composites will necessitate the development of more advanced technologies for their machining in the future as researchers continue to look for more effective means with which to machine these composites without having a deleterious impact on their properties. Major conclusions from the current study can be drawn are:

- Among several existing manufacturing processes, WEDM emerged as the most convenient and advantageous for fabricating metal matrix composites as recent technological improvements were brought into the process.
- Processing using WEDM for MMCs was greatly impacted by the type of reinforced material used, and these influenced MRR and Ra during the processing. While selecting for reinforcement, great care must be taken care for the intended machining process results.
- To improve the rate of production and lower surface roughness, parameters should be optimised for the material, most researchers have shown an interaction between factors that clearly indicate the necessity to use optimised parameter settings to avoid material and time wastage.
- As WEDM involved thermal heating during process, some group of researchers drew attention on wire breakage issue during processing, that further highlights use of machine learning based algorithm to predict and avoid such situations.

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