Fabrication of Metal Matrix Composites: A Systematic Review

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Abstract: Metal matrix composites (MMCs) are essential materials in various fields of application due to their excellent properties, including high strength-to-weight ratio, high corrosion resistance, wear resistance, and adaptability. Their continuous progress in their manufacturing techniques created these properties. This helps to meet the growing demand for sustainable and high-performance products. The two industries most likely to benefit are the automotive industry and the aerospace industry, where MMCs are used for lightweight, strong parts in automobiles, airplane frames and jet engines. Further, because of their suitable mechanical properties and corrosion resistance, MMCs are extensively used in biomedical applications for implants and medical devices. These are used in heavy construction, in defense and even in space exploration. The composite industry has evolved dramatically in the last twenty years with MMC materials due to their improved mechanical, tribological and metallurgical properties. This review paper introduces and examines the most recent advances (mostly from the last 5 years) in MMC- fabrication techniques. Process factors affecting the properties and microstructure of the composites are presented as well as the innovation and modernisation of both conventional and advanced techniques. The assessment is based on properties and potential applications of MMC which have been greatly improved and extended by these developments. The latest methods used for the fabrication of MMCs are discussed, including the friction stir processing (FSP), ultrasonic assisted stir casting and additive manufacturing. The machine learning and artificial intelligence interventions for composite manufacturing also are discussed in this review. This article aims to aid researchers and academics and encourage them to conduct further research and innovation to further develop the space.

Keywords: *MMCs; Stir Casting; Powder Metallurgy; Additive Manufacturing; FSP; Machine Learning.*

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I. INTRODUCTION

➢ *Overview of Metal Matrix Composites*

Metal matrix composites (MMCs) are a class of materials comprising a metal or alloy matrix reinforced with particles, whiskers, fibers, or hollow micro balloons. The rein-forcement materials, which can be metallic, ceramic, or polymeric, are added to boost mechanical properties, thermal stability, and wear resistance of the base metal. When compared to other composites, MMCs have a distinct set of properties. Among all MMCs, some composites are perfect for applications in a diversity of industries, including auto-motive, aerospace, and transportation, since they have a high strengthto-weight ratio, a low thermal expansion coefficient, and great wear and abrasion resistance [1]. MMCs can offer better property combinations than traditional composites, particularly when hybrid MMCs with various reinforcements are used. MMCs are energy-saving materials that are widely employed because of their acknowledged capacity to deliver required qualities such as tensile strength, stiffness, hardness, and fatigue and wear resistance [2].

Since the transition from monolithic metals to advanced materials such as MMs, a variety of materials with high temperature resistance, specific stiffness and specific strength have been developed MMCs [3]. This makes MMCs indispensable engineering materials in various industries such as automotive, aerospace, defense industry and marine industry. Additionally, MMCs have self-healing properties, which enhances the life and reliability of the material, especially in aircraft applications [4]. MMCs have been made by several processes for their synthesis and production. In the manufacture of MMCs, precise control of the distribution of reinforcement particles within the metal matrix is crucial for numerous reasons. The properties of MMCs, such as strength, stiffness, and toughness, are greatly affected by the distribution of reinforcing components. The properties are enhanced by uniform distribution, but if the distribution is not uniform, high stress concentrations or isolated weakness can reduce the overall performance of the composite. In many manufacturing techniques like casting, additive manufacturing, and more, accurate distribution of reinforcement is crucial to ensure the product's quality and uniformity. For example, by using selective laser fusion (SLM), the mechanical properties are enhanced by

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controlling the distribution of the fibres in a desired manner. A homogenous distribution of reinforcements is necessary to achieve the desired qualities in MMCs. If uniformity is desired for the application, non-uniform distribution may lead to variations in material properties between the different components of the composite material. The reinforcing elements should be in contact with the metal matrix. The optimal interface bonding is influenced by the strength and durability of the composite, achieved by precise control of the distribution. A lot of techniques were applied to improve results, but the first one was to have an easy to use, affordable and effective way to process where the characteristics would be altered. The selection of the appropriate fabrication method is of paramount importance since it influences the microstructural features such as distribution, orientation and interfacial attachment of reinforcements and matrix [5]. Research papers provided can be the basis of several possible options to improve the efficiency of the manufacturing process of MMC. An overview of MMCs with the applications and fabrication processes is presented in Figure 1.

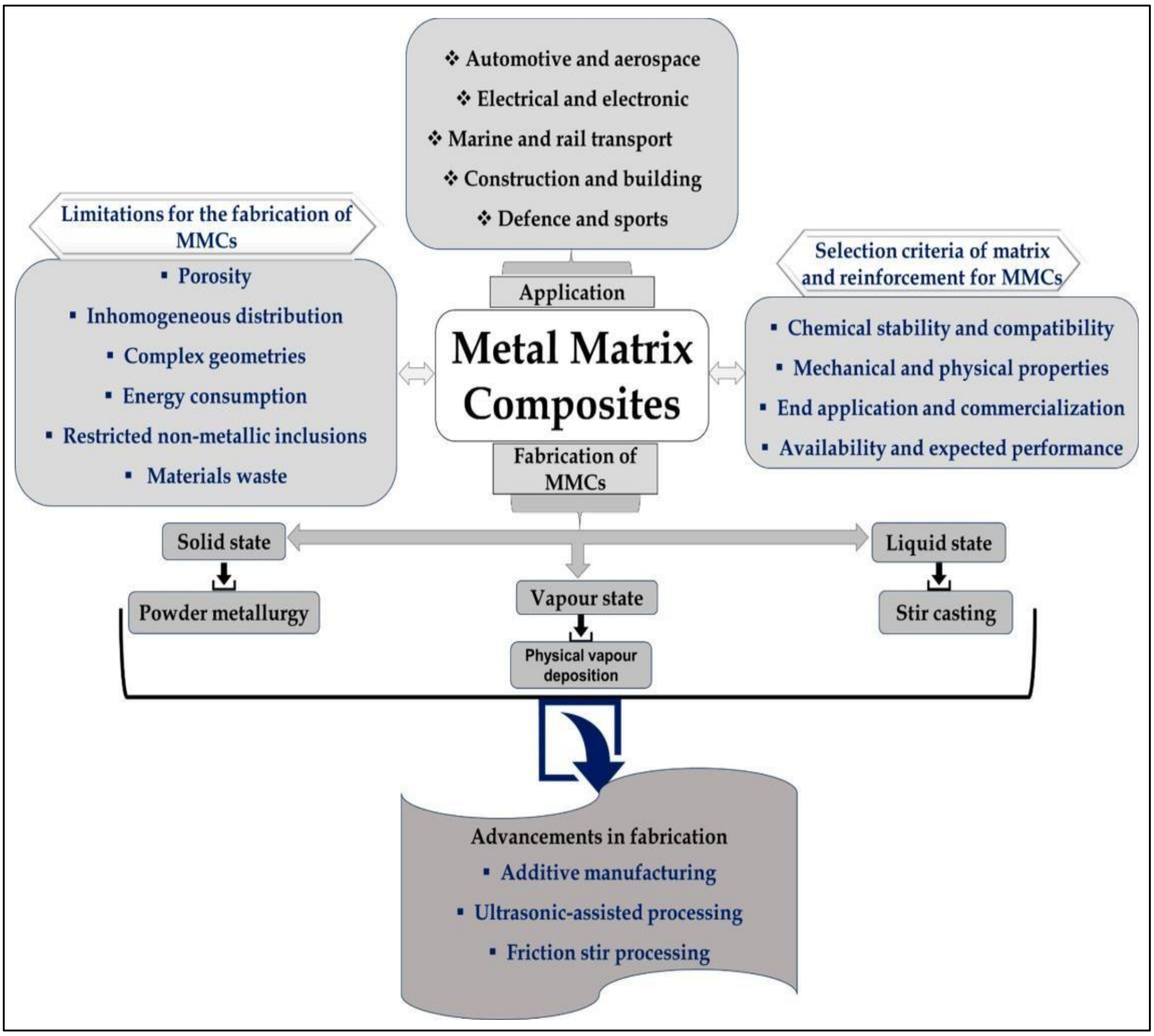

Fig 1 Overview of Fabrication of Metal Matrix Composites.

These processes have pros and cons depending on the specifications and features of the final product. Liquid state, solid state, and vapor state processes are three groups into which the basic techniques are divided. The existing approaches to MMC fabrication suffer from the issues of traditional manufacturing process like liquid or powder metallurgy, such as lack of adequate wettability of the particles by the molten metal, settling or floating of particles due to the difference in their densities and the formation of unwanted intermetallic particles [6]. In addition, the establishment of a weak zone along joint lines restricts the size of the components that can be created when MMCs are joined by fusion welding. Stir casting and powder metallurgy are the two main manufacturing methods used for producing MMCs, however, for overcoming these limitations and scaling up the production of MMCs, the need for advanced manufacturing technique like additive manufacturing (AM) is emphasized [7]. This emphasizes the need to address technical issues in future applications of MMCs. One of the most important factors influencing MMCs' performance during the intricate preparation process is their structure. Mechanical properties of the MMCs are significantly

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influenced by the distribution, size and nature of reinforcement as well as the matrix material in the structure. Performance is impacted by the structure in the following significant ways:

- *Mechanical Properties:*

- ✓ *Strength and stiffness:* Reinforcements like fibers or ceramic particles are added to MMCs to increase their strength and stiffness. The load is transferred from the matrix to the reinforcements because they are often stronger and stiffer than the matrix material.
- ✓ *Toughness:* The kind and distribution of reinforcement have an impact on the toughness of MMCs. Uniformly placed reinforcements can improve durability by preventing cracks from spreading.

- *Wear Resistance:*

- ✓ *Surface hardness*: The hardness of the reinforcing components, like ceramic particles, increases the wear resistance of MMCs. A well-dispersed reinforcing structure can generate a harder surface that reduces wear during operation.
- ✓ *Load distribution:* A homogeneous distribution of reinforcements contributes to a more even distribution of the load by reducing localized stress concentrations and boosting wear resistance.

- *Thermal Properties:*

- ✓ *Thermal conductivity:* MMCs' thermal conductivity is influenced by their structural face, namely the kind and arrangement of reinforcements. For example, adding carbon fibers can improve MMCs' heat conductivity.
- ✓ *Thermal expansion:* The coefficient of thermal expansion (CTE) of MMCs is influenced by the reinforcing structure. By reducing the thermal expansion mismatch between the matrix and reinforcements, a well-designed structure can enhance dimensional stability.

- *Fatigue Performance:*

- ✓ *Crack initiation and propagation:* The structure of MMCs, especially the contact between the matrix and reinforcements, affects how well they withstand fatigue. Strong interfaces can improve fatigue life by preventing crack initiation and propagation.
- ✓ *Load transmission:* The ability of the reinforcements to effectively transfer load to the matrix is a crucial aspect of fatigue performance. A well-bonded contact reduces the likelihood of fatigue failure and ensures effective load transmission.

- *Corrosion Resistance:*

- ✓ *Protective layers:* When building MMCs, protective coatings or layers on the reinforcements can be added to boost corrosion resistance. For example, coatings can prevent galvanic corrosion between the matrix and reinforcements.
- ✓ *Barrier effect:* Corrosive agents may find it more difficult to permeate the matrix material when reinforcements are evenly distributed.

- *Processing and Manufacturability:*

- ✓ *Flow properties:* The size and shape of the reinforcements during processing, particularly lar, affect MMCs' flow characteristics. Smaller particles have better flowability, making it easier to produce a uniform distribution.
- ✓ Defect formation: Two types of defects that the structure may impact are agglomeration and porosity. Advanced production techniques, including as friction stir casting and ultrasonic-assisted stir casting, improve the overall quality and performance of MMCs by minimizing these defects.

- *Interface Properties:*

- ✓ *Bonding strength:* The interaction between the matrix and reinforcements is crucial to MMCs' efficacy. A strong contact ensures better mechanical properties and efficient load transfer.
- ✓ Chemical compatibility: The matrix and reinforcements' chemical compatibility affects the interface's characteristics. Advanced processing techniques can help improve interfacial bonding, which will enhance MMCs' overall performance.

II. REVIEW METHODOLOGY

The first phase in the review process is to define the objectives and scope of the study, which is focused on examining the most recent advancements in MMC fabrication during the previous five years, with a particular emphasis on improvements in solid and liquid processes. The scope also covers cutting-edge methods for creating MMCs. To begin the literature search, a list of specific keywords was created, such as "Advancements in fabrication of MMCs" and "Novel techniques for fabrication of MMCs." These keywords were used in the search process throughout the most significant academic databases, including Scopus and Google Scholar. The search technique included an initial wide search using particular keywords, which yielded a substantial number of research publications from various disciplines. This method limited the results to studies that directly addressed the developments in MMC fabrication over the preceding five years.

The results required to be assessed and framed in relation to the article's contents in order to synthesize the reviewed literature. This entailed broadening the scope from conventional approaches to cutting-edge processes used in MMC production. Finding the benefits and drawbacks of each fabrication method was a crucial part of the methodology. The analysis provided recommendations for this evaluation in order to help academics and industry experts with high-quality MMC products.

In order to provide an inclusive and comprehensive search, the technique strongly emphasized the importance of

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accurately defining search parameters and avoiding the omission of crucial information. The search technique was designed to be both general and specific enough to yield relevant results while encompassing a wide number of relevant studies. This approach was necessary to provide a thorough and precise examination of the most current advancements in MMC fabrication.

In conclusion, the methodology of this review article employs a mixed systematic approach to the search, appraisal, and synthesis of the literature. By highlighting recent advancements and the incorporation of cutting-edge processes for the manufacturing of MMCs over the conventional methods, the approach aims to provide insightful analysis and expand the body of knowledge in the industry.

➢ *The Following is a Summary of this Review's Objectives:*

- To gather and examine literature on recent implementations for the fabrication of MMCs over the previous five years, with a focus on improving the quality of composite products.
- To examine the outcomes and determine how the latest developments help to achieve good-quality MMCs with enhanced physical properties.
- To recognize and explore the effects of fabrication parameters on MMCs in the existing literature concerning their applications in various industries.
- To present a thorough synthesis of the results and provide an in-depth understanding of the major issues, developments, and trends in advancements for fabrication of MMCs.

III. ADVANCES IN FABRICATION METHODS OF MMCS

➢ *Advances in Solid-State Processes*

Due to the increasing demand worldwide, MMCs are utilized in a wide range of industries. MMCs may have the appropriate properties if the proper reinforcing materials and production methods are used [8]. The most used method is powder metallurgy (PM), which is based on solid phase processing. Because mixing and densification are straightforward, this usually has discontinuous reinforcements [9]. Metal particles are combined, statically cold-compressed, then heated to achieve the maximum density. This can occur under controlled settings through mechanical alloying, in a dry environment, or with the use of dispersion agents. The majority of the time, PM activities are conducted at moderate temperatures, and there is little to no interaction between the reinforcement and matrix components [10]. While uniformly dispersing reinforcing phases within the matrix phase might give composites better mechanical properties, the insertion of short fibers or whiskers may need the employment of small particles to increase the scattering and filling of the microstructure. MMCs have traditionally been made using PM. It entails compression and sintering after mixing metal powders with reinforcing elements. High-energy ball milling to improve reinforcing particle distribution and the use of spark plasma sintering (SPS) for quicker and more effective consolidation are two recent developments in PM. PM has a lot of potential for creating MMCs because it provides greater control over the material's microstructure and properties than conventional methods provide [11]. Better mechanical qualities and increased resistance to deformation are the outcomes. The solidstate MMC production process is shown in Figure 2.

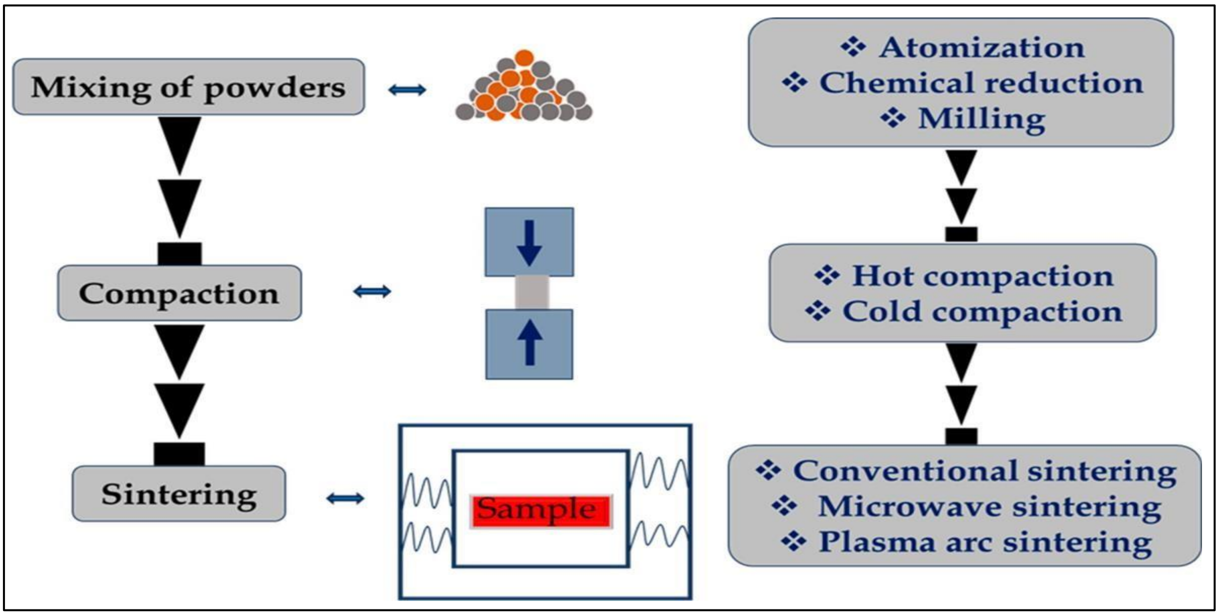

Fig 2 Illustration of Solid-State Fabrication of MMCs.

The PM process is a useful and economical method of creating MMCs with superior mechanical and tribo-logical properties [12]. A careful selection of process parameters, such as compaction pressure, sintering time, and temperature, can lead to improved mechanical and tribological properties of the composites. Researching the mechanical and wear properties of particle-reinforced MMCs is essential. Novel and advanced strategies used in the PM process for MMCs

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include powder blending, surface modification, optimized sintering parameters, advanced consolidation techniques, and the development of new strategies like double pressing-double sintering (DPDS) and hot pressing (HP). By dispersing powder evenly, enhancing bonding across surfaces, preventing particle agglomeration, controlling porosity, and ensuring proper dispersion of reinforcement, these tactics and methods aim to address challenges encountered during the production of MMCs. Additionally, the use of hybrid reinforcements like as graphene (Gr) and carbon nanotubes (CNTs) enhances the field of MMC construction. Copper-graphite composites with good mechanical properties can be made using PM and conventional sintering methods [13]. Wear resistance increases by 88% as the percentage of Gr grows. Microhardness and compressive strength reach their maximum at 1% Gr concentration, after which they begin to decrease. Sterioudi et al. [14] successfully created an AA 2024 alloy composite reinforced with MWCNTs using mechanical alloying, milling, and two distinct powder metallurgy techniques, DPDS and HP. The best mechanical properties were obtained using the HP technique, but at 2 weight percent MWCNT content, clustering resulted in a sharp decline in performance. Both the DPDS and HP procedures provided improved mechanical qualities when comparing the AA2024/MWCNT nanocomposites to pure AA2024; however, the HP approach produced better mechanical properties overall due to their higher density and finer grain. The dramatic drop in mechanical properties that happened when the MWCNT level surpassed 2 weight percent was caused by the MWCNTs' inhomogeneous dispersion and clustering. Both techniques can produce nanocomposites with a good balance between strength and ductility. The AA2024-2 weight percent MWCNT nanocomposite created by the DPDS method had a compressive strength of 350 MPa and 16% elongation, but the identical nanocomposite produced by the HP method had a compressive strength of 423 MPa and 19% elongation.

The effects of aging and PM process parameters on the wear and hardness properties of Al 6063 MMCs reinforced with varying volumes of nano Al2O3 particles were investigated by Haque et al. [15]. The wear rate of the Al6063-nano Al2O3 MMCs lowers with increasing nano Al2O3 adding percentage; the lowest wear rate is seen at 8% nano Al2O3 composition. To reduce wear rate and increase microhardness, the optimal processing parameters are 550 MPa of compaction pressure and 60 minutes of compaction time. The microhardness of the MMCs increases up to a 6% addition of nano Al2O3, but it falls at an 8% addition. Ni-base MMCs are designed for use in spaceship mechanical seals and were produced using PM hot isostatic pressing [16]. The volume proportion of ceramic reinforcement (SiC or TiB2) in the IN625 matrix was found to be significant; higher fractions led to better hardness and tribological properties. Two mechanical seal demonstrators were successfully fabricated using IN625-10%SiC, which was determined to have the best combination of tribological properties, machinability, and hardness. Tribo-mechanical characteristics of self-lubricating hybrid MMCs based on Al and reinforced with Gr and Al2O3 were investigated by Zamani et al. [17]. The tribological and mechanical properties of the hybrid MMCs are significantly superior to those of the base materials, especially those containing 10% and 3% Al2O3 and Gr. The addition of Al2O3 significantly improved the tribological properties of an Al-Gr composite, including wear rate and coefficient of friction (COF), as well as its mechanical properties, including hardness, tensile strength, and flexural strength. Nayak et al. [18] investigated four different hybrid composite samples made by mixing aluminum powder with different ratios of Al2O3 and SiC in order to gain a better understanding of the mechanical and physical properties of Al-based MMCs produced using PM. Following an hour of ideal sintering at 700 °C, materials containing the combination of (Al/2%SiC/3%Al2O3) and (Al/7%SiC/3%Al2O3) showed improved mechanical properties and density.

Excess reminder additions (>3% Al2O3, >8% SiC) led to poor sinterability and reduced density, hardness, and compressive strength.

TiO2 was used to build Al-based MMCs using PM techniques, and the material's mechanical and microstructure characteristics were examined in order to create a robust, lightweight, and reasonably priced material [19]. The Al-TiO2 composites' compressive strength increased from 67.90 MPa to 77.53 MPa and their Brinell hardness increased from 19.51 BHN to 26.08 BHN when the TiO2 concentration grew from 0 to 12 weight percent. For braking applications, the mechanical properties of AlSiC functionally graded materials (FGMs) are employed [20]. Four-layered FGM specimens showed better mechanical properties and a more homogeneous microstructure than five-layered specimens. Brittleness and a reduction in the material's toughness can result from over-reinforcement of SiC in the Al matrix. Al-Mg MMCs enhanced with a PM method and micro-sized SiC or Al2O3 particles were prepared and analyzed by Tosun and Kurt [21]. The highest porosity ratio was 17% for the 15% SiC/Al-Mg composite produced at 300 MPa and 400 ◦ C for 90 minutes, while the lowest porosity ratio was 5.4% for the 15% SiC/Al-Mg composite produced at 600 MPa and 500 ◦ C for 90 minutes. The microhardness of 15% SiC and Al2O3/Al-Mg composites decreased when the sintering temperature was raised from 300 to 400 degrees Celsius. For 15% SiC and Al2O3/Al-Mg composites, reaching 500 °C during the sintering process enhanced microhardness. As the sintering temperature increased, the microhardness of 30% SiC/Al-Mg composites decreased. Rising sintering temperatures lead to agglomeration inside the structure and increased formation of the Al4C3 phase. The clustering of the reinforcement reduces the number of microparticles. As a result, the strength and microhardness dropped. Al-Mg composites are harder than SiC/Al-Mg composites because SiC is harder than Al2O3.

In a different study, Parveen et al. [22] produced Al-based hybrid composites reinforced with Si3N4 and ZrO2 using a PM technique. By increasing the milling time and weight percentage of the nano-ZrO2 reinforcement, the Al-Si3N4/ZrO2 composite demonstrated better density and hardness, decreased porosity, and more homogeneous

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particle dispersion. The addition of WC and SiC reinforcements improved the hardness, wear resistance, and corrosion resistance of copper matrix composites [23]. The Cubase matrix's electrical conductivity was improved by the addition of alloying elements. Cu improves the corrosion resistance of composites. AZ91 matrix composites with 10, 20, and 30% TiB2 were successfully produced by HP [24]. In terms of mechanical properties, wear resistance, and hardness, the composites fared better than the unreinforced AZ91 alloy. Although there was some partial agglomeration at 30%, the TiB2 particles were evenly dispersed. Because of micropores, the composites' relative density dropped as the TiB2 concentration rose, but their hardness and wear resistance significantly increased. The ultimate compressive strength and compressive yield strength rose with TiB2 concentration up to 20%, although the failure strain of the composites was more than that of the AZ91 alloy. The Al matrix was considerably toughened while maintaining its exceptional strength and flexibility when a substantial volume of 60% glassy particles based on Fe was utilized as reinforcement [25]. The composites achieved high relative densities of 97–98% with comparatively few pores, demonstrating effective densification without adverse consequences at the matrix– reinforcement interfaces. A microstructural analysis found that while the Al+4wt%SiC composite showed the most uniform distribution of reinforcement, higher SiC levels led to agglomeration [26]. The hybrid composite Al+4wt.%SiC+2wt.%B4C showed a homogenous structure and the best interfacial bonding between matrix and reinforcement. The Al+4%SiC+2%B4C hybrid composite had the highest compressive strength under both 5N and 10N loads, while the Al+5%SiC+2%B4C hybrid composite had the lowest wear rate. HP and PM techniques were successfully used to generate Mg/B4C composites with 10, 20, and 30% B4C [27]. The addition of B4C particles greatly improved the composites' hardness, wear resistance, and compressive yield strength; the Mg/30 weight percent B4C composite exhibited the best wear resistance.

From 10 to 20% SiC content led to greater corrosion rates and better resistance to pitting corrosion when analyzing the corrosion behavior of Al/SiC composites manufactured utilizing PM techniques [28]. The pitting corrosion resistance of Al/SiC composites improved with increasing SiC (10–20%) content, which was previously associated with homogeneous deterioration in chloride environments. The PM technique was used to create and characterize Al-based MMCs reinforced with SiC and

Al2O3 particles [29]. Aluminum’s compressive strength was increased by adding SiC and Al_2O_3 reinforcements; however, adding more reinforcements than the recommended 7% SiC and 3% Al_2O_3 resulted in poor sinterability. Increasing the sintering period from 30 to 90 minutes improved the density, hardness, and microstructure of the Al/7% SiC composite; the compressive strength of the Al/SiC/alumina hybrid composites was unaffected. Al2O3 and ZrO2 ceramics were used in the PM method to produce and reinforce Al-based MMCs [30]. The hardness of the MMCs increased as the weight percentage of the ceramic reinforcements increased, and the Al-ZrO2 composites were harder than the Al-Al2O3 composites. Impact velocity and impingement angle were found to be significant determinants in the semi-ductile and semi-brittle erosion wear behavior of the composites. The 5 weight percent ZrO2 reinforcement was found to be the best of the composites analyzed. A 5-vol% SiC/AA2024 nanocomposite was made using PM, and the optimal production conditions were discovered to yield the best tensile properties [31]. By increasing the ball milling time from 12 to 24 hours, the microstructure and SiC nanoparticle dispersion were enhanced. The hardness, yield strength, and ultimate tensile strength of the 5-vol% SiC/AA2024 nanocomposite all significantly increased as a result. PM was used to reinforce AA7075 metal matrix composites with 4, 6, and 10 weight percent SiC particles [32]. The porosity, density, compressive strength, and hardness of the AA7075-SiC metal matrix composites all improved as the SiC content rose from 0% to 10%. PM was used to generate Cu-B4C MMCs. The Cu-B4C composites' hardness, relative density, and compressive strength all increased as the B4C component climbed to 15 weight percent [33].

There was good compatibility between the copper matrix and the uniformly dispersed B_4C particles.

➢ *Advances in Liquid-State Processes*

This method allows for the fabrication of MMCs by incorporating a metal matrix in liquid form into or with the reinforcement particles. The most advanced liquid phase processing techniques fall into a number of categories. One method for creating MMCs is infiltration, which involves melting a matrix under pressure and injecting liquid metal into a porous preform while keeping the reinforcing phase intact. The application of pressure and vacuum depends on the type of reinforcement and weight percentages. This process is used to create Al-based composites even though the final product may contain some porosity and areas with reinforcing material. Superior microstructures and minimal chemical interaction are present in the reinforcing and matrix interphase. Among the main advantages of the infiltration method are the possibility of creating near-net-shaped products and their application with a range of reinforcement materials. Pressure infiltration or pressureassisted liquid infiltration of a fibrous or particle material are other names for squeeze casting. Using an extrusion die and tremendous pressure, liquid metal is compressed into virtually net-shaped products during the squeeze casting process [34]. Manufacturing uses both direct and indirect squeeze casting procedures. In the indirect method, a runner system is used to supply the melt into the die. In direct squeeze casting, the melt is inserted into the die using a tiny shot piston, and pressure is applied to the melt using a runner system. Popular variations like stir casting and squeeze casting have been improved with better mold designs and infiltration methods to improve interfacial bonding and reinforcement distribution. Stir casting is the method used to create MMCs reinforced with fibers and particles [35]. It is sometimes referred to as a vortex or slurry casting since composites are created by creating a vortex. Some stir casting methods use ultrasonic stirring for improved results. Reinforcement materials are properly mixed and applied to the molten metal

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to prevent the fibers or particles from aggregating. The mixture is then either poured into a second die with the proper size or left to cool in the crucible without the mixing arm. It should be noted that adding reinforcing components may increase the viscosity of the molten metals, and this growth in viscosity depends on the proportion of the reinforcement and may make mixing more difficult. Due to the segregation, the finished product could have an uneven microstructure.

Solid-phase and liquid-phase manufacturing techniques are the main methods used to create Al-based MMCs [36]. The most popular, least expensive, and mass-producible processing technique for making MMCs is stir casting. MMCs can be constructed with exceptional properties that are difficult to achieve with monolithic materials by combining the proper components. Due to their improved properties, such as their ductility, low weight, and high strength-to-weight ratio, MMCs have been developed for a number of applications, including high-temperature, automotive, aerospace, and defense [37]. Although fiber-reinforced composites provide the most gains in strength and stiffness, particulate-reinforced composites exhibit more isotropic behavior. Reinforcements such SiC, Al2O3, TiO2, and graphite improve the mechanical properties of Al-MMCs produced by stir casting. Higher hardness and ultimate tensile strength (UTS) are two of these characteristics. Stirring length and stirrer speed are crucial factors affecting the production of Al-based MMCs (AMCs) using the stir casting method, as they determine the uniform dispersion of reinforcement particles in a molten metal matrix [38]. The quality of the casting is affected by pouring temperature, reinforcement size, mold–crucible distance, and pouring rate, all of which prevent gas from becoming trapped. By adding alloying ingredients and heating the reinforcement and mold, the wettability between the reinforcement and matrix is altered. Several state-of-the-art methods have been employed to enhance the properties of MMCs produced by stir casting. Improving mechanical qualities like strength and hardness by modifying manufacturing parameters like stirring temperature, time, and speed is one of these methods. In an attempt to increase the dispersion of the reinforcing phases inside the matrix, the effect of stirrer blade design on particle distribution is also investigated. Furthermore, the incorporation of ceramic particles into the molten matrix alloy to maximize wettability and yield in MMCs has been investigated through liquid state and semisolid state mixing processes, demonstrating advances in the stir casting technique for the fabrication of components for various industries.

To improve MMCs' mechanical properties, such as hardness and grain structure, ceramic reinforcements like Al2O3 and SiC can be added [39]. Stir-casting technique limitations such as temperature, stirring speed, and duration must be optimized in order to achieve a uni-form dispersion of the reinforcements and minimize defects. In order to enhance the mechanical properties of the Al alloy, Fenghong et al. [40] looked into the development and assessment of hybrid composites composed of an Al-based matrix reinforced with WC and SiC particles. In contrast to monolithic Al-alloy, SiC, and WC reinforce-ment particles greatly increased hardness of the Al-based hybrid composites. The hybrid composites outperformed the monolithic Al alloy in compressive strength due to the addition of stiffer reinforcing particles. The wear resistance and mechanical qualities of MMCs made of magnesium and reinforced with fly ash at weight percentages of 2.5, 5, and 7.5% were superior to those of pure magnesium [41]. Tensile strength and hardness of Mgfly ash composites were increased by up to 42% and 21%, respectively, when compared to pure Mg; samples with 7.5 weight percent fly ash showed the best results. Using the stir casting method, AA6061 alloy matrix composites rein-forced with 15 and 20 wt.% Si_3N_4 were produced satisfactorily [42]. There were no visible indications of porosity or other casting flaws, and the Si_3N_4 particles were consistently dispersed throughout the Al alloy matrix. In comparison to parent AA6061 alloy, Si_3N_4 reinforcement greatly improved the composites' microhardness and UTS. A stir casting process was employed to examine impacts of reinforcing Al6061 alloy with 5 wt.% Fe_2O_3 and 2–6% B_4C [43]. Al6061 alloy matrix was supplemented with 5% constant Fe_2O_3 and 2–6% variable B_4C to increase the composite material's hardness, compressive strength, tensile strength, and microstructural homogeneity. The performance and characteristics of hybrid metal matrix composites (HMMCs) are greatly impacted by rejection phenomena. The rejection of BN-coated SiC particles from aluminum alloys emphasizes how important ceramic particle stability is in molten metal, which can affect the composite's reinforcement's uniformity and effectiveness. Particle agglomeration and wettability issues can arise from the use of some manufacturing techniques, particularly liquid-state processing, which can worsen the rejection phenomenon and perhaps degrade material properties. Additionally, interfacial interactions may alter the matrix and weaken reinforcements during processing, endangering the mechanical integrity of the composite. Despite these challenges, given the correct processing circumstances, HMMCs— particularly those reinforced with materials like SiC and B4C—have shown improved me-chanical properties, indicating that careful control of rejection events can lead to better composites. Therefore, in order to maximize HMMC effectiveness, rejection events must be fully understood and managed.

An optimal composition of 7% SiC improves the mechanical, tribological, and microstructure properties of the AMCs, according to another study that looked at the effects of adding SiC reinforcement to Al5083 aluminum alloy [44]. The addition of 7 weight percent SiC improved the microhardness by 55%, the ultimate tensile strength by 29%, and the tribological characteristics and wear resistance by 25% when compared to the original Al 5083 alloy. While Al 1100 reinforced with SiC composites changed 0–15 weight percent in 5% increments, it was discovered that adding SiC reinforcement to the Al matrix gradually enhances hardness and UTS from 23 HV to 47 HV and 84 MPa to 130 MPa, respectively [45]. Please modify this sentence as 'Adding $AlTiB_2$ master alloy to molten Mg alloy enhanced hardness, yield strength, UTS, and elongation by 16.1%, 53.0%, 26.3%, and 25.6%, respectively [46]. In the maritime industry and marine conditions, Al 2024 with SiC and $ZrSiO_4$ MMCs

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greatly increases the wear resistance of the as-synthesized matrix alloy; SiC is responsible for the material's improved surface hardness, and $ZiSiO_4$ for its improved bonding strength [47].

IV. NOVEL AND MODERN METHODS FOR MMC FABRICATION

Currently, several cutting-edge processes are being used to fabricate MMCs due to the rising demand for the products made from them. The goal of advanced and novel approaches like selective laser melting (SLM), friction stir processing (FSP), wire arc additive manufacturing (WAAM), and ultrasonic-assisted processing methods is to improve the mechanical potentials and processability of MMCs [48]. For example, a combination of substrate modification in AM and SLM was proposed to create dense, high-strength, and crack-free MMCs for industrial applications. However, FSP methods, such as robotic wirebased FSP, use pre-plasticization procedures and paraxial feeding wires to lower the axial force needed for making complicated parts with good mechanical characteristics and little force. Additionally, by focusing on material flow, stress evolution, and microstructure creation during MMC processing, ultrasonic-assisted processing techniques provide insights into parameter-dependent mechanics and physical behaviors for improved part quality. The operating principles of some new innovative techniques used for MMC manufacture are depicted in Figure 3. Some of the more sophisticated techniques that attempt to solve the shortcomings of the traditional methods of creating MMCs include AM, FSP, and ultrasonic-assisted stir casting. High melt viscosity, particle agglomeration, and challenges sintering to a high relative density are among the disadvantages of traditional methods like stir casting and powder metallurgy. Early MMC component failure and uneven reinforcement distribution are common outcomes of stir castinginduced particle agglomeration. However, by using friction stir techniques and ultrasonic waves to improve the dispersion of reinforcing particles, FSP and ultrasonicassisted stir casting improve the homogeneity and uniformity of MMCs. High melt viscosity makes it difficult to achieve a uniform reinforcement distribution in stir casting, which can also lead to defects like porosity. By precisely controlling the microstructure, AM techniques lower flaws and raise the overall quality of MMCs. The high cost of PM procedures and their challenges in sintering MMCs to a high relative density raise the total processing expenses. With AM, it is possible to create almost net-shape components straight from raw material, which lowers costs and eliminates the need for intensive secondary processing. Defects like porosity and particle agglomeration are a problem for both stir casting and PM processes, and they can affect the mechanical characteristics of MMCs. By enhancing the dispersion and distribution of reinforcements, FSP and ultrasonic-assisted stir casting methods aid in the reduction of these flaws. The capacity to create intricate forms is constrained; therefore, the design and fabrication of MMC components are highly difficult. The opportunity to create complicated components straight from CAD models is made possible by AM, which enables more creative freedom and the production of intricately shaped components. A summary of recent novel techniques applied for the fabrication of MMCs with the findings is depicted in Table 1.

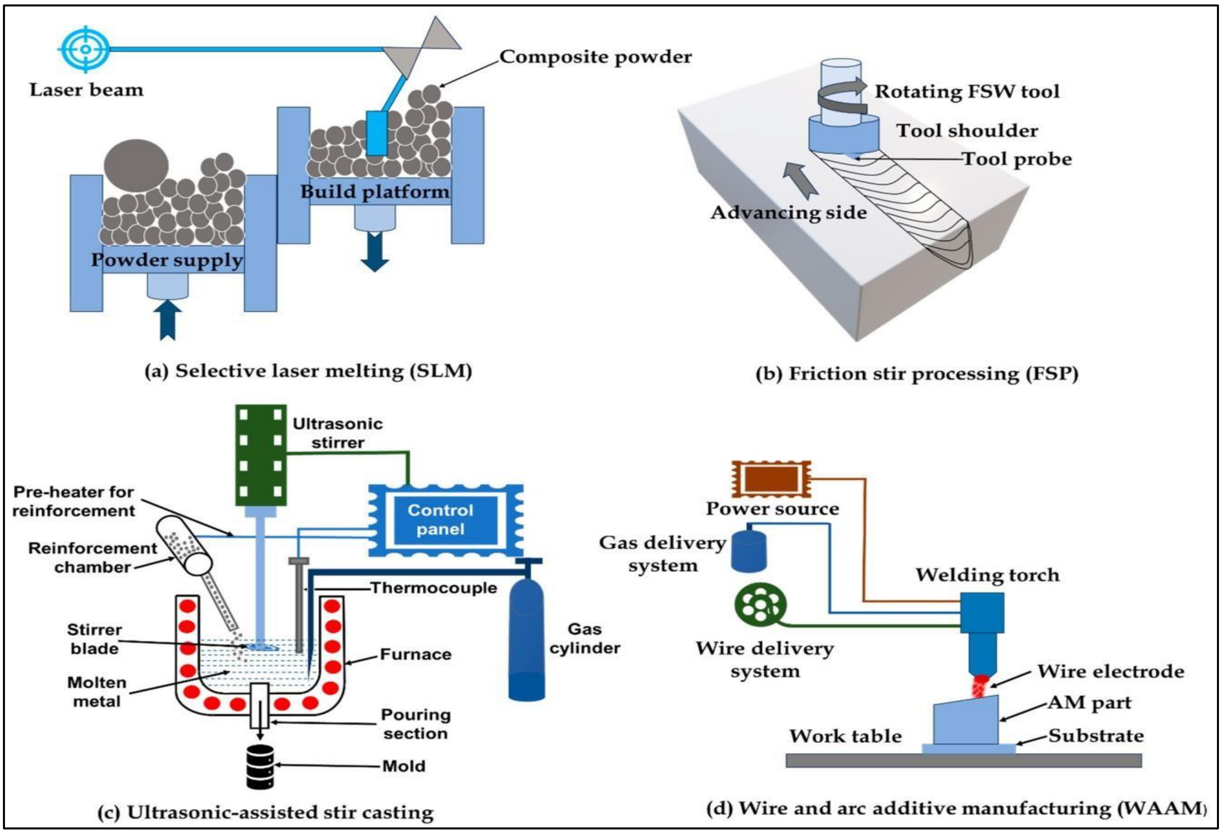

Fig 3 Schematic Representation of Various Novel Fabrication Techniques for MMCs.

For metallic materials, laser additive manufacturing (LAM) and other additive manufacturing (AM) processes offer a number of benefits as well as future development potential [49]. Excellent material utilization, rapid prototyping, personalization, and the ability to construct complex structures are some of the benefits of AM, especially LAM. While laser metal deposition (LMD) offers higher production efficiency, selective laser melting (SLM) components perform better in terms of manufacturing precision and material consumption rate. The proper selection of process parameters in laser deposition-additive manufacturing (LD-AM) can raise the melting point and homogenize the properties of the manufactured parts while reducing the detrimental effects of excessive thermal stress and component deformation [50]. The LD-AM method shows that it is possible to treat ceramics with high hardness and melting points as well as ceramic-reinforced metal matrix composites. Additionally, it can be applied to bulk materials as cladding layers to enhance surface characteristics or incorporate chemical or biological components. A framework for using AM to produce inexpensive porous titanium alloy matrix composites for orthopedic implant applications was developed by Attar et al. [51]. It explains how these materials are made using alloy composition design, computer-aided structural design, manufacturing optimization, and reinforcing methods. The goal is to create titanium composite orthopedic implants with improved structural compatibility and longer lifespans. ZrB2-fortified Inconel 718 (In718+ZrB2) superalloy MMCs were created using a new technique called laser powder bed fusion (LPBF) [52]. Although elongation was somewhat decreased, Inconel 718+ZrB2 performed 10% to 15% better than pure Inconel 718 in terms of strength. Additionally, at 800 °C, the ZrB2 reinforced composite demonstrated a significant increase in ductility compared to pure In718, attaining roughly 10% elongation while maintaining better strength. These results suggest that the production of MMCs doped with ZrB2 may significantly increase Inconel 718's ability to tolerate high temperatures and may even raise the maximum operating temperature limit in systems that now employ Inconel 718 components.

Additive printing may be used to create metallic materials with site-specific microstructures, but in order to fully realize this potential, a comprehensive understanding of microstructure development is necessary [53]. The hierarchical microstructures found in metals made additively fall into two categories: solidification structures and postsolidification structures. Because of the fast cooling rates in additive manufacturing, supersaturated solid solutions are created that provide additional strength. The laser power and scan speed were the main factors affecting the densification behavior of Al-based nanocomposites treated by SLM [54]. Because of their high compaction and ultrafine microstructure, SLM-processed CNTs/Al-based nanocomposites demonstrated remarkable microhardness, tensile strength, and elongation when using ideal SLM settings of 350 W laser power and 2.0 m/s scan speed. The better mechanical qualities were shown to be caused by three strengthening mechanisms: grain refinement, Orowan looping, and load transfer. Single-layer Ti-based MMCs reinforced with WC particles were effectively constructed using a novel method, paraxial powder injection technology based on wire and arc additive manufacturing (WAAM) [55]. The results demonstrated that the WC particles were distributed in a gradient across the layer's depth and that droplet transmission was unaffected by injecting the powders from the rear of the molten pool. The particles and matrix formed a strong metallurgical bond.

In ultrasonic-assisted processing, high-frequency vibrations are employed to improve the dispersion of reinforcing particles inside the metal matrix. It has been shown that this technique enhances the mechanical properties of MMCs by reducing porosity and enhancing the interfacial interaction between matrix and reinforcement. The mechanical and physical characteristics of AMCs produced by conventional stir casting and ultrasonic-assisted stir casting were compared [56]. AMCs' tensile strength, compressive strength, and hardness increased when SiC particles were introduced. When using the ultrasonic-assisted stircasting approach instead of the conventional stir-casting method, these attributes were also better. The electromagnetic stir-squeeze casting technique, when combined with bottom pouring attachments and an ultrasonic probe, is the most promising processing method for MMCs. Recent research has evaluated the advantages of ultrasonic vibrations on the uniform distribution of reinforcements and the ensuing improvements in mechanical and tribological features in the manufacturing of Mg-based MMCs (MMMCs) utilizing ultrasonic-assisted stir casting [57]. Despite having a lot of potential for usage in automotive and aerospace applications, magnesium-based alloys are not commonly used due to their weak strength, ductility, and wear resistance. The mechanical and tribological characteristics of the MMMCs are enhanced by applying ultrasonic vibrations during the production process to obtain a uniform distribution of the reinforcement particles and decrease the metal matrix's grain size. A good method for obtaining unvarying spreading of nanoparticles in MMCs is ultrasonic cavitation [58]. Using the ultrasonic cavitation approach, alumina-dispersed aluminum nanocomposites are deprived of discrimination. The utilization of ultrasonic cavitation technology during synthesis of alumina-dispersed aluminum metal matrix composites results in enhanced mechanical and structural characteristics. The development and wear performance of AZ91 Mg matrix composites were improved using Al_2O_3 particles produced by stir casting with ultrasonic aid. The development and wear performance of AZ91 Mg matrix composites were improved using Al_2O_3 particles produced by stir casting with ultrasonic aid [59]. Al_2O_3 particles were uniformly dispersed by ultrasonic agitation, which improved the wear resistance of the Al_2O_3/AZ91 composites. The two most important variables influencing the composites' wear behavior were sliding distance and normal load. The composite with a surface smoothness and wear resistance of 1.5 wt.% Al_2O_3 content was the best. The microstructural and mechanical properties were evaluated by incorporating micro and nano Al_2O_3 particles into an A356 Al alloy matrix that was manufactured by stir casting and ultrasonic stirring [60]. Strengthening dislocations and reducing grain size, the inclusion of ceramic particle reinforcements, particularly

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nano-Al_2O_3, improves mechanical properties of AMCs. The inclusion of 0.5 wt.% nano-Al_2O_3, which had the highest ultimate tensile strength and elongation, resulted in the best mechanical characteristics. Kumar and Kumar [61] investigated effects of T6 heat treatment on properties of base alloy and fabricated composite, as well as microstructural, mechanical, and tribological characteristics of a hybrid AMC that was manufactured utilizing ultrasonicassisted stir casting with ZrB_2 and fly ash as reinforcements. The AMC grain refinement was significantly enhanced by the addition of ceramic reinforcements (ZrB_2 and fly ash). The T6 heat treatment greatly increased the composite's tensile strength; 5% ZrB_2 composite demonstrated a tensile strength improvement of 70% over the as-cast composite and a 10% increase over the as-cast base alloy. With a very low COF and strong wear resistance, a composite containing 5% ZrB_2 demonstrated outstanding tribological characteristics under lubricated circumstances, making it a viable option for use in structural, automotive, and aerospace applications.

An ultrasonic-assisted casting method was utilized to fabricate an Al6061 alloy reinforced with 2 wt.% SiC and different concentrations of Gr (0–3 wt.%) [62]. In contrast to Al6061 alloy, hybrid nanocomposites' wear rate and COF dropped by as much as 73% and 17.7%, respectively. Using an ultrasonic-assisted stir casting technique, frivolous and wearresistant AZ91D MMMCs were created and reinforced with TiB_2 [63]. The most important factor was stirrer speed, followed by ultrasonic power and reinforcement concentration. The optimum combination of low wear and high microhardness was achieved with the following ideal parameters: 1500 W ultrasonic power, 3 wt.% TiB_2 concentration, and 400 RPM stirrer speed. While fabricating AA6061-B_4C MMCs using ultrasonic-assisted stir casting, a composite containing 4 wt.% B_4C had the best mechanical properties, outperforming unreinforced AA6061 matrix by 36.32% in specific UTS, 43.92% in specific compressive strength, 53.41% in specific Vickers hardness, and 50.89% in specific Brinell hardness [64]. Hybrid reinforced composites with varying wt.% of SiC and palm sprout shell ash (PSSA) (0:0, 0:4, 1:3, 2:2, and 4:0 wt.%) were fabricated using the ultrasonic-assisted bottom-poured stir casting technique [65]. The 2:2 wt.% SiC and PSSA hybrid reinforced composites showed a notable improvement in both tensile and flexural strength, with increases in strength of 29.15% and 27.64%, respectively, among all composites.

Friction stir processing (FSP) is a solid-state processing technique that utilizes a nonconsumable rotating tool to stir the metal and reinforcement materials, resulting in a fine-grained and homogenized structure. Recent advancements in FSP include the development of multi-pass processing and the integration of ultrasonic vibrations to further refine microstructure and improve mechanical characteristics of MMCs. FSP is an efficient technique for creating AMCs with enhanced mechanical and tribological characteristics [66]. Many processing factors have an impact on the characteristics of the composites made by FSP. Because various Al alloys have varied metallurgical and structural characteristics, their responses to identical FSP processing conditions might vary dramatically. When compared to traditional methods, FSP has become a widely used approach for creating composites and functionally graded systems with better attributes [67]. For sophisticated engineering applications, FSP is a widely used technology to create hybrid MMCs with various reinforcements in addition to mono-reinforced MMCs [68]. The mechanical, hardness, and strength characteristics of MMCs can be amended by adding carbon nanotubes (CNTs) as reinforcements using FSP [69]. The qualities of the finished composite are significantly influenced by the FSP process parameters, which include the number of passes, feed rate, tool rotation speed, and quantity of reinforcement. Additionally, the wear performance, cold formability, and corrosion behavior of the composite may all be enhanced by adding CNTs to the metal matrix. Butola and Murtaza [70] observed how microhardness of AA7075 surface composites was affected by FSP parameters such as tool profile, reinforcements, and tool rotation speed. They found that the most important parameter was tool rotation speed, with 1000 rpm being the ideal speed, and that the best reinforcement for increasing microhardness was B_4C, which elevated the microhardness of the AA7075 composite by 1.5–1.6 times. With eggshell waste material and $SiC/Al_2O_3/Ti$ reinforcement, parent metal AA7075 alloy has favorable properties for FSP [71]. The following process settings are ideal for creating a high-quality FSP composite: tilt angle= 2°, tool speed = 2250 rpm, and reinforcement = Ti + eggshell.

The self-assembled monolayer (SAM) method and FSP were used to add B_4C nanoparticles, which resulted in a noticeable (more than two-fold) increase in hardness and a minor drop in ductility for the AA6063/B_4C nanocomposite [72]. Because the AA6063/B_4C nanocomposite contained hard B_4C particles, it exhibited better wear resistance than the unreinforced FSPed sample. The B_4C nanoparticles were distributed uniformly across the treated region thanks to the SAM approach, which also produced consistent mechanical characteristics. FSP was used to effectively create MMCs based on Al, Mg, and copper, using fly ash (FA) as the reinforcement [73]. The FA particles were equally distributed throughout the metal matrix without agglomeration or segregation because the FSP approach efficiently stirred them. After the addition of FA particles, the microhardness of all the composites increased. When SiC particles were embedded utilizing FSP techniques, the microhardness of Al2024 alloy was increased by up to 50% with uniform SiC particle spreading and grain refinement [74]. FSP significantly boosted the yield strength of the Al2024 alloy by a factor of around 2.5, and the addition of SiC particles further improved the yield strength of the MMC sample. Faster rotation speeds lead to increased fragmentation in cold-sprayed (CSed) AA2024/Al2O3 MMCs, while FSP makes the Al2O3 particles more distributed and refined [75]. The top surfaces of the friction stir processed (FSPed) MMCs have the maximum level of hardness and refinement, and they display graded microstructure and mechanical characteristics. FSP improves the tensile charac-teristics (UTS and elongation) of the CSed MMCs, and it can improve them even more at faster rotation rates. FSP improved the microstructure and mechanical characteristics of coldsprayed AA2024/Al2O3 MMCs; improved interparticle attachment and dispersion consolidation from advanced Al2O3 elements

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were the main strengthening mechanisms. The presence of weak interparticle connections continues to be the main barrier inhibiting further improvement of tensile properties, however more FSP passes may help strengthen the composites even more. Sharma et al. [76] used FSP to examine the wear characteristics of aluminum 7075 alloy reinforced with B_4C particles. They discovered that the ideal settings are 1600 RPM and 30 mm/min feed rate. Because of the consistent distri-bution of the B_4C particles, AMC created by including them had greater wear resistance than both the base material and FSPed alloy without particles. In an innovative way, gas pressure infiltration was successfully used to create a novel interpenetrating MMC with an open porous metallic glass lattice structure, reinforcement phase composed of an alloy composition of $Ni_{60}Nb_{20}Ta_{20}$, and matrix material, eutectic AlSi12 [77]. The z-direction strength of the $Ni_{60}Nb_{20}Ta_{20}$-AlSi12 MMC is 430.51 MPa, whereas the x- and y-directions have 280.11 MPa. The MMC reinforced with metallic glass exhibits much-increased strength compared to the pure AlSi12 matrix.

The potential to increase composite material production efficiency is demonstrated by artificial intelligence (AI) [78]. AI and other digital techniques were used to address flaw identification in composites, curing composite materials, simulation, and process control for composite manufacturing [79]. The variety of applications for composite materials may be expanded by these developments in AI approaches for creating composites with intricate and customized structures [80]. Forward models were created using machine learning (ML) approaches, mainly connecting processing parameters to MMC properties [81,82]. ML algorithms have been used to predict the properties of metal-matrix composites using composition factors like size and reinforcing particle weight percentage as well as processing parameters from various manufacturing processes like casting, powder metallurgy, and mechanical alloying. ML approaches can be applied to microstructural analysis and process improvement in addition to quality prediction [83]. The impact of important process variables on the mechanical performance of stir-cast magnesium metal composites (Mg-MMCs) was optimized using response surface methodology (RSM) and artificial neural network (ANN) approaches [84]. The variable that had the biggest impact on the mechanical properties of the final composites was the weight percentage of particles. The optimal parameter values for maximal mechanical qualities were found at 312.8 rpm, 11.9 min of stirring time, and 9.9 weight percent SiC particle, according to the desirability function technique. An ANN model was used in another investigation to map the tensile strength and hardness of stir-cast MMCs against Al6061 alloy and various weight percentages of reinforcements [85]. The results show that the proposed model has the potential to replace traditional experimental approaches and reduce the cost and time needed for the study of aluminum composites due to its low mean squared error (0.0058606) and regression value (0.96118) around unity.

Al alloy was hybridized with Si3N4, Al2O3, and TiC nanoparticles in a ratio of 94% primary material to 6% reinforcing material using a stirring-squeeze casting process [86]. With a casting die temperature of 400 °C and a squeezing pressure of 100 MPa, the Knearest neighbor (KNN) and gray wolf optimization (GWO) algorithm-based optimization produced a material with a tensile strength of 134.75–159.50 MPa and a hardness of 80.75– 82.92 HBN. ANN-predicted squeeze pressure of 100 MPa, melt temperature of 750 ◦ C, die temperature of 250 ◦ C, and pressure holding time of 10 s produced the best results for AA6061/Al2O3/SiC/Gr composite made by squeeze casting in terms of maximum hardness (131 HVN) and tensile strength (329 MPa) in other significant work [87]. The combination of ANN-GA technique was applied to optimize the ultrasonic casting condi-tions for the development of Al-TiB_2 MMCs [88]. With an error of 2.85%, the developed model demonstrated high accuracy in porosity prediction. The minimal porosity value was 3.88, which corresponds to the ideal casting parameters of a horn depth of 70 mm in the melt, a duration of 20 min for ultrasonication, and a melt temperature of 662.5 ˚C for ultrasonication. The results indicated that the combined ANN-GA approach may be used to increase the industrial application of particulate Al-based MMCs.

Table 1 Summary of Some Novel and Advanced Techniques Applied for Fabrication of MMCs.

Reference	Material and Technique	Findings
[54]	Al/CNT; Selective laser melting	High microhardness of 154.12 HV and a tensile strength of 420.8 MPa.
[55]	Ti/WC; Wire and arc additive manufacturing (WAAM)	Strong metallurgical bonds between the particles and the matrix were produced with the cost-effective WAAM and paraxial WC powder injection.

Table 1. Cont.

Reference	Material and Technique	Findings
[59]	AZ91D/Al_2O_3; Ultrasonic-assisted stir casting	29.23% greater wear resistance and 43% higher hardness compared to the AZ91 Mg matrix alloy.
[60]	Al-A356/ micro-Al_2O_3, nano-Al_2O_3; Ultrasonic-assisted stir casting	A356 matrix composites containing nano-Al_2O_3 showed superior mechanical characteristics compared to micro-Al_2O_3 particles.
[61]	AA7075/ZrB_2/Fly Ash; Ultrasonic-assisted stir casting	The specific wear rate was reduced by 46.94% for the fabricated hybrid Al-based MMCs as compared to the base alloy.
[62]	Al6061/2SiC-xGr; Ultrasonic-assisted stir casting	The wear rate and COF of hybrid nanocomposites decreased by up to 73% and 17.7%, respectively.

[63]	AZ91/TiB_2; Ultrasonic-assisted stir casting	The ultrasonic agitation of the liquid melt caused uniform dispersion of TiB_2 reinforcement particles in the composites, which consequently improved the composites' microhardness and wear.
[64]	AA6061/B_4C; Ultrasonic-assisted stir casting	The ultrasonication enabled the improvements in specific UTS (36.32%), specific compressive (43.92%), specific VH (53.41%), and specific BHN (50.89%) at such a low 4 wt.% of B_4C.
[65]	Al-Cu-Mg-alloy/SiC/palm sprout shell ash (PSSA); Ultrasonic-assisted stir casting	With improvements in the strength of 29.15% and 27.64%, respectively, among all composites, 2:2 wt.% SiC and PSSA hybrid reinforced composites demonstrated a significant improvement in both tensile and flexural strength.
[70]	AA7075/B_4C/SiC/Rice Husk Ash (RHA); Friction stir-processing (FSP)	AA7075/B_4C composite was found to be 1.5–1.6 times stronger than the base metal; B_4C was determined to be the most effective reinforcement when compared to SiC and RHA. AA7075/RHA composites exhibited 11% greater microhardness values than the base metal.
[71]	Al 7075/eggshell waste material/ SiC/Al_2O_3/Ti; FSP	At the ideal process parameters, RF = Ti + Egg Shell, TS = 2250 rpm, and TA = 20, a range of hardness values was observed for the FSP of the A7075 alloy, using eggshell waste as well as SiC/Al_2O_3/Ti reinforcement.
[72]	AA6063/B_4C; Self-assembled monolayer (SAM) method and FSP	FSPed AA6063/B_4C nanocomposite showed superior wear resistance due to the presence of hard B_4C particles. The SAM technique achieved enhanced mechanical properties and homogenous distribution of B_4C nanoparticles across the treated area.
[73]	AA6061/AZ31, copper/ fly ash; FSP	Regardless of the type of matrix material utilized, FSP is an appropriate technique to generate fly ash-reinforced MMCs.
[74]	Al2024/SiC; FSP	SiC particles embedded in FSPed samples increased microhardness by 50% over the as-received state.
[75]	AA2024/Al_2O_3; FSP	UTS and elongation of the cold sprayed (CSed) AA2024/Al_2O_3 MMCs were enhanced by FSP, with UTS and elongation increased by up to 27.4% and 25.9%, respectively.
[76]	AA7075/B_4C and FSP	Ideal parameters of the FSP process, 1600 rotating speed and 30 mm/min feed rate, yielded better wear resistance for the AA7075/B_4C composites compared to the base material.

Table 1 Cont.

Reference	Material and Technique	Findings
[77]	AlSi12/$Ni_{60}Nb_{20}Ta_{20}$; Gas pressure infiltration process	MMC reinforced with metallic glass exhibits substantially better strength than the pure AlSi12-matrix. The strength of AlSi12/$Ni_{60}Nb_{20}Ta_{20}$ MMC is 280.11 MPa in the x and y directions and 430.51 MPa in the z direction.
[84]	AZ91/SiC; Stir casting with RSM and ANN approaches	Desirability function analysis showed that 312.8 RPM stirring speed, 11.9 min stirring duration, and 9.9 wt% particle were the ideal parameter conditions for maximal mechanical characteristics. According to ANN and RSM analysis, the wt. % of particles has the greatest influence on the mechanical characteristics of the composites.
[85]	Al 6061/SiC, Gr, Talc, Al_2O_3, Fly ash, B_4C; Stir casted through ANN modelling	With an overall regression (R) value of 0.96118, the model predicted UTS and hardness with a mean squared error of 0.0058606, respectively.
[86]	AA2219/TiC, Al_2O_3, Si_3N_4; Stir-squeeze casting with K-nearest neighbor (KNN) and grey wolf optimization (GWO) approaches	Improved tensile strength ranging between 134.75 and 159.50 MPa, and improved hardness ranging between 80.75 and 82.92 HB.
[88]	Al-TiB_2; Ultrasonic stir casting with ANN, GA approaches	The lowest porosity value of 3.88, which corresponds to the optimal casting parameter, was obtained after applying ANN-GA.

V. CONCLUSIONS

This review aimed to provide new knowledge related to advancements in the fabrication of MMCs. By examining the state-of-the-art techniques for MMC fabrication, advancements therein, and identifying areas for future research, the paper contributes to the body of knowledge so that future research and development can be pursued by scholars, researchers, and engineers to establish the field further. With the use of several methods such as powder metallurgy and stir casting, the production of MMCs has advanced significantly. These techniques have made it possible to fabricate MMCs with improved mechanical properties, including increased impact resistance, hardness,

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compressive strength, and tensile strength. Through intensive research, issues related to particle agglomeration, densification, and wettability in MMC production have been resolved, resulting in the development of standardized and sophisticated composite materials. The fabrication of MMCs has seen significant advancements, with traditional techniques being refined and novel methods emerging. The precise control over microstructure and composition offered by these advanced fabrication techniques has the potential to unlock the full potential of MMCs, leading to materials with superior properties for high-performance applications.

The following conclusions can be drawn after analyzing advancements in the fabrication of MMCs:

- Powder metallurgy is gaining popularity as a viable substitute for traditional sand casting and offers several advantages over it, particularly in terms of refining composite potentials. Stir casting is a popular fabrication process for MMCs because of its ease of use, adaptability, and affordability for mass industrial production.
- The aerospace, defense, transportation, and power generating industries have all benefited greatly from advancements in solid-state techniques for manufacturing MMCs. But compared to approaches like powder metallurgy, advances in solid-state techniques like friction stir processing ensure better dispersion of reinforcements, higher densification, and improved interfacial bonding, which eventually produce MMCs with superior physical properties.
- Liquid state processing techniques for MMC production have yielded considerable improvements in terms of ease of use, reduced costs, and enhanced material characteristics. Improvements in MMC fabrication have made it possible to fabricate MMCs
- with improved tensile, wear, and metallurgical properties in spite of the drawbacks of traditional liquid state methods, such as insufficient particle wetting and the creation of undesired intermetallic particles. The prospective applications of MMCs in sectors such as aerospace, defense, transportation, and power generation have been extended due to these improvements.
- The production of specific parts in industries like aerospace and healthcare has been made possible by advances in additive manufacturing (AM), particularly in metal 3D printing techniques like selective laser melting (SLM). The use of AM techniques for manufacturing MMCs has benefits in terms of cost, time efficiency, precision, and quality.
- In terms of microstructure and mechanical qualities, the ultrasonic-assisted stir casting process has proven to be significantly superior to conventional stir casting processes. It has been concluded that using ultrasonic vibration during the casting process can improve the mechanical properties of MMCs by refining grain size and promoting a more uniform dispersion of reinforcing particles.
- In comparison to conventional processes, the friction stir processing technique fabricates composites that are more promising for a variety of applications due to better strength, hardness, and ductility.
- The fabrication of MMCs is greatly improved by the ANN, GA, and machine learning type intelligent techniques. This leads to improvements in property prediction and process optimization. This technical development is essential to producing highperforming materials with specific applications.
- The development of MMCs using recycled resources, such as borosilicate glass and scrap aluminum, exemplifies a waste-reduction strategy that maximizes mechanical qualities without sacrificing sustainability. This approach encourages ecologically friendly behaviors, which not only enhances material performance but also supports the sustainable development goals.
- Utilizing low-energy sintering techniques in regulated environments can result in low-cost, high-performing composites with decreased porosity. The future of the industry depends on reducing waste and optimizing resource utilization, which in turn supports a circular economy.

The possible future research avenues include accelerating attempts towards employing machine learning for intelligent modeling and optimization, life cycle engineering and analysis of processes, incorporating environmentally benign activities, and utilizing industrial wastes for novel and advanced MMCs fabrication.

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➢ *Nomenclature*

Aluminum oxide	Al_2O_3
Boron carbide	B_4C
Carbon nanotubes	CNT
Copper	Cu
Graphite	Gr
Silicon carbide	SiC

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Al-based MMC	AMC
Additive manufacturing	AM
Coefficient of friction	COF
Double pressing-double sintering	DPDS
Friction stir processing	FSP
Hot pressing	HP
Silicon nitride	Si_3N_4
Titanium diboride	TiB_2
Titanium oxide	TiO_2
Tungsten carbide	WC
Zirconium oxide	ZrO_2
Computer aided drafting	CAD
Mg-based MMC	MMMC
Selective laser melting	SLM
Weight percentage	wt.%
Metal matrix nanocomposites	MMNCs
Ultimate tensile strength	UTS
Friction stir processing	FSP

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