

Review

Advances in the Design and Development of Lightweight Metal Matrix Composites: Processing, Properties, and Applications

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Abstract

Lightweight metal matrix composites (MMCs) continue to attract significant interest due to their potential to deliver high mechanical performance at reduced weight, meeting the increasing demands of aerospace, automotive and advanced manufacturing sectors. Among these systems, aluminum-, magnesium- and titanium-based MMCs stand out for their favorable strength-to-weight ratios, corrosion resistance and versatility in processing. Although numerous studies have explored individual MMC families, the literature still lacks comparative reviews that integrate quantitative mechanical data with a broad evaluation of processing, microstructural control and application-driven performance. This review addresses these gaps by providing a comprehensive and data-driven assessment of lightweight MMCs. Recent advances in reinforcement strategies, hybrid architectures and processing routes—including friction stir processing, powder metallurgy and semi-solid techniques—are systematically examined. Emerging developments in syntactic metal foams and functionally gradient MMCs are analyzed in detail, along with practical considerations such as machinability, corrosion resistance, and high-temperature performance, integrated with AI/machine learning for predictive optimization. Overall, this work provides an integrated and critical perspective on the capabilities, limitations, and design trade-offs of lightweight MMCs, positioning them as sustainable and high-performance alternatives for extreme environments. By combining qualitative insights with quantitative meta-analyses and new experimental contributions, it offers a valuable reference for researchers and engineers seeking to optimize material selection and tailor the performance of MMCs for next-generation lightweight structures, surpassing previous reviews through holistic and innovation-driven insights.

Keywords: lightweight metal matrix composites; nanostructured reinforcements; ceramic particles; additive manufacturing; powder metallurgy; advanced structural materials



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1. Introduction

The development of lightweight metal matrix composites (MMCs) has gained significant momentum in recent years, driven by the increasing need for materials that combine low density with superior mechanical, thermal, and functional performance. Sectors such as aerospace, automotive, defense and advanced manufacturing continuously seek material solutions capable of meeting stringent requirements for weight reduction, energy efficiency, sustainability and performance under complex loading conditions. In this context,

MMCs based on aluminum, magnesium and titanium matrices have emerged as promising candidates due to their favorable strength-to-weight ratios, corrosion resistance and manufacturability. Reinforcements such as silicon carbide (SiC), aluminum oxide (Al_2O_3), boron carbide (B_4C), carbon nanotubes (CNTs), graphene and other nanostructured phases are widely incorporated to enhance tensile strength, stiffness, wear resistance and thermal stability while maintaining a lightweight profile [1,2].

Parallel to the development of advanced reinforcements, significant progress has also been made in MMC processing routes. Techniques such as friction stir processing, semi-solid forming, powder metallurgy, stir casting and additive manufacturing enable tighter control of microstructure and more uniform dispersion of reinforcements [3–6]. These advances mitigate long-standing challenges including reinforcement agglomeration, porosity, weak interfacial bonding and undesirable reaction phases. Hybrid reinforcement strategies—combining ceramic, carbon-based and metallic particles—have also gained relevance, enabling synergistic strengthening mechanisms and improved multifunctionality [7–11].

The increasing use of MMCs is visible across a broad range of applications. In aerospace and automotive engineering, lightweight MMCs are already employed in braking systems, structural supports, chassis elements and high-temperature components where fatigue, wear and thermal stability are critical [12,13]. Their growing relevance aligns with global priorities related to fuel savings, CO_2 reduction, sustainability and enhanced service life of engineering systems [14,15]. Figure 1 illustrates examples of lightweight MMC components designed for automotive applications [16].

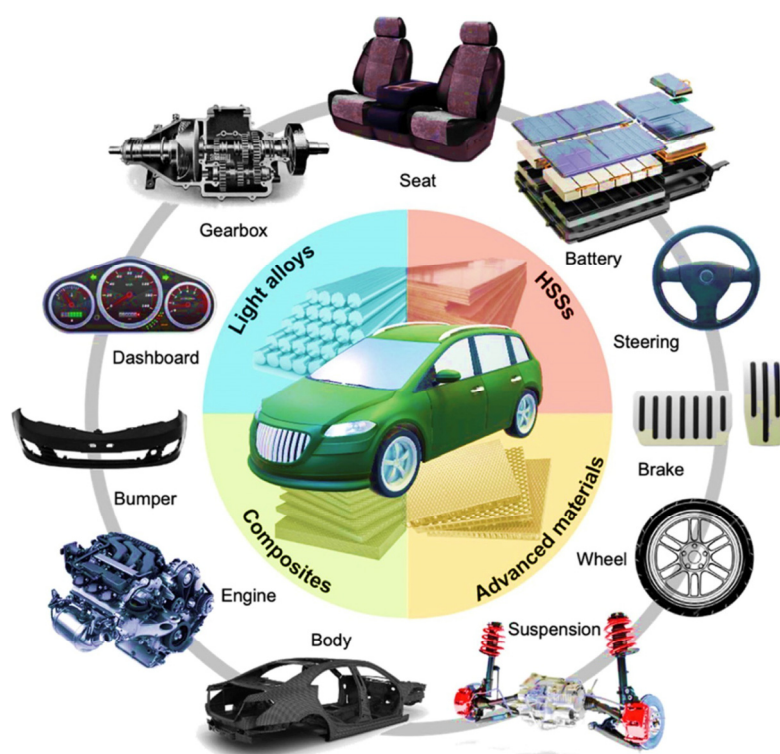


Figure 1. Illustrative diagram of lightweight alloy applications for use in vehicle components. Reprinted from Ref. [16].

Despite the breadth of existing literature, several gaps remain in current reviews, particularly concerning the comparative performance of Al-, Mg- and Ti-based MMCs under different loading conditions, their machinability, and the emerging classes of syntactic and functionally graded foams. Many published reviews focus on a single matrix system or

emphasize processing routes without establishing cross-material relationships, quantitative comparisons or mechanical trends. Additionally, properties under dynamic loading (impact, fatigue, high strain rate), high-temperature exposure or corrosive environments are often insufficiently discussed, even though they dictate the practical adoption of MMCs in real-world applications.

To address these gaps, the present review provides a comprehensive and data-driven comparative assessment of lightweight MMCs, focusing specifically on aluminum, magnesium and titanium matrices. Beyond summarizing recent advances in processing routes and reinforcement strategies, the review incorporates a statistical meta-analysis of more than fifty peer-reviewed studies to enable quantitative comparisons of tensile strength, stiffness and hardness across different MMC families. It further includes a detailed examination of quasi-static, dynamic, fatigue and impact behavior to support a more complete understanding of mechanical performance under service-relevant conditions. Additionally, the review expands the discussion on metal syntactic foams and functionally graded MMCs, emphasizing technological developments that are often overlooked in earlier studies. Finally, it integrates insights into machinability, corrosion resistance and high-temperature performance—factors that are critical for industrial adoption but seldom examined in a unified manner.

Overall, this review aims not only to summarize the recent progress in lightweight MMCs but also to provide a critical, integrative and comparative perspective that enhances the understanding of their capabilities, limitations and emerging technological pathways.

2. Matrices and Reinforcements for Lightweight MMCs

Lightweight metal matrix composites (MMCs) have gained significant attention due to their ability to deliver high mechanical efficiency while maintaining reduced structural weight, a combination essential for aerospace, automotive, defense and advanced manufacturing systems. In these composites, the matrix not only serves as the load-bearing continuum but also dictates key characteristics such as ductility, thermal conductivity, fatigue resistance and response to dynamic loading. Aluminum (Al), magnesium (Mg) and titanium (Ti) remain the most widely adopted matrices due to their excellent strength-to-weight ratios, corrosion resistance and processing versatility.

Reinforcement selection—whether ceramic particles, whiskers, hollow spheres, carbon-based nanomaterials or hybrid systems—plays a fundamental role in tailoring stiffness, hardness, thermal stability and wear resistance. The synergy between matrix and reinforcement is central to achieving the multifunctional behavior required in applications subjected to fatigue, impact, high strain rates and elevated temperatures. Consequently, a critical and integrated understanding of matrix–reinforcement interactions is essential for designing MMCs capable of satisfying increasingly demanding performance requirements.

2.1. *Metallic Matrices*

2.1.1. Aluminum Alloys

Aluminum alloys are one of the most widely used materials as a matrix in lightweight MMCs due to their advantageous mechanical properties, low density, and wide processing flexibility [9,10,12]. In this class, the AA6061, AA7075, and AA2024 alloys stand out due to their excellent strength-to-weight ratios and suitability for demanding industrial environments, particularly in the aerospace and automotive sectors [17,18]. Due to these characteristics, these alloys have an attractive combination of superior tensile strength, strong corrosion resistance, and robust fatigue behavior, making them ideal candidates for the inclusion of multiple ceramic or particulate materials in reinforcement applications [17,18]. It is of utmost importance to optimize the selection of the aluminum alloy for the composite. For

example, in the AA7075, a zinc-rich alloy well known for its strength. Its main application is in the aerospace industry, where the need to reduce weight while preserving structure is a necessity [17,19]. On the other hand, AA6061 is used in structural components due to its excellent weldability [20,21], as well as its combination of mechanical strength and thermal stability.

These alloys typically benefit from the addition of ceramic reinforcements, such as silicon carbide (SiC), aluminum oxide (Al_2O_3), and boron carbide (B_4C), which enhance strength and hardness while maintaining low density. The synergistic effects of the matrix and the reinforcements confer enhanced mechanical properties and thermal stability to the MMCs [22,23]. In addition, novel processing methods, like ultrasonic stir casting and high-pressure die casting, have emerged to ensure the incorporation of such reinforcements in aluminum matrices can be achieved with high efficiency [19,24]. Such techniques facilitate to address some common problems of conventional casting methods, including particle agglomeration and poor matrix reinforcement bonding that can weaken the mechanical properties of composites [17,24]. These novel strategies have been applied at uniform spacing of reinforcements that have achieved superior yield strength, ultimate tensile strength and wear resistance [19,24].

In addition to traditional reinforcements, nanomaterials such as carbon nanotubes (CNTs) and graphene have been studied for the advancement of aluminum alloys. When these nanostructured materials are integrated, they can considerably improve the thermal and mechanical properties of the composites formed, thus increasing their functionality for highly efficient applications [25,26]. Notably, the introduction of CNTs into aluminum alloys has been shown to improve electrical and mechanical properties due to their nanoscale properties [25]. MMCs are produced by high-pressure die casting (HPDC) of aluminum in this work, where MWCNTs are included in the short sleeve. In the second step, the cast ingot undergoes 10 extrusion cycles (EC) to separate the MWCNT agglomerates and orient them for extrusion. An illustrative drawing of the MMC processing steps is provided in Figure 2.

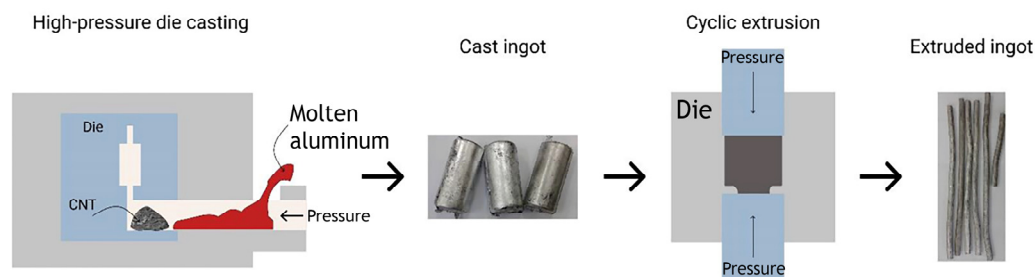


Figure 2. Illustrative draw of the production of the MMCs of the Al reinforced with CNTs. Reprinted from Ref. [25].

Figure 3 shows the results of electrochemical impedance spectroscopy (EIS). From these graphs, they provide useful information about the corrosion mechanisms affecting both the 1070 aluminum alloy (sample A) and the Al-MWCNT composites (samples B and D). Two capacitive loops are visible in the Nyquist plots at high and intermediate frequencies, and a characteristic inductive loop can be seen at low frequencies. The high-frequency capacitive loop is often related to charge transfer occurring at the metal/oxide interface, which shows an electrochemical profile of the passive film on the material surface.

Simões et al. [26] demonstrate CNT dispersion in aluminum via ultrasonication, achieving uniform distribution and 50% hardness increases, with HRTEM showing embedded CNTs and Al_4C_3 formation. Carneiro and Simões [27] report 185% yield strength gains in

Al/CNT nanocomposites via powder metallurgy, attributed to load transfer, while reducing ductility due to CNT clusters.

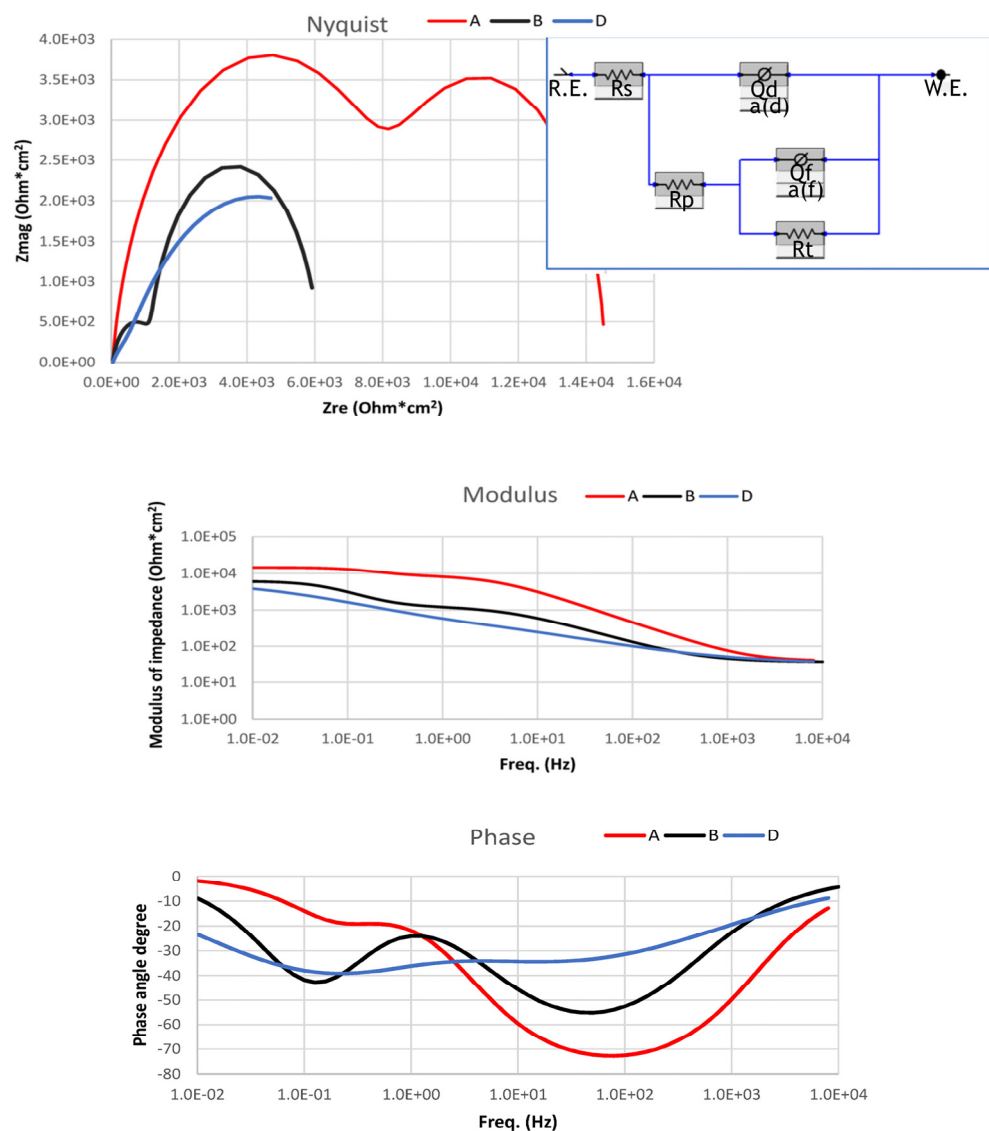


Figure 3. Electrochemical impedance spectra of sample A—pure aluminum 1070; sample B—Al 1070 + 0.25 wt. % MWCNTs; and sample D—Al 1070 + 0.5 wt. % MWCNTs. Reprinted from Ref. [25].

In addition, aluminum alloys play an important role in the production of lightweight MMCs. The recyclability of aluminum alloys, accompanied by environmentally friendly reinforcements, including natural fibers or agricultural waste, is one of the crucial steps towards more environmentally friendly manufacturing in the composite materials segment [28,29]. Consequently, attempts are underway to optimally characterize the construction of the aluminum alloy-reinforcement mixture for composites that meet high-performance standards for industrial uses and serve to increase environmental sustainability.

Aluminum alloys remain a key material in the field of lightweight metal matrix composites. Their inherent properties, when combined with suitable reinforcements and advanced processing techniques, lead to the creation of high-performance materials that are suited for a wide range of applications in various industries.

To provide a comprehensive overview, the mechanical and physical properties of Al-based CMMs are summarized in Table 1. This table compares the main properties (tensile

strength, hardness, density, and thermal conductivity) for Al-based MMCs, highlighting the improvements over unreinforced matrices.

Table 1. Properties of Al and Al-based MMCs.

Matrix/Reinforcement	Tensile Strength (MPa)	Hardness (HV)	Density (g/cm ³)	Thermal Conductivity (W/m·K)	
AA6061	310 ± 15	105 ± 5	2.70	167	[17]
AA6061 + 10% SiC	420 ± 20	140 ± 8	2.75	160	[22]
AA7075 + 5% CNTs	550 ± 25	180 ± 10	2.72	175	[25]
AA2024 + Hybrid (SiC + CNTs)	480 ± 18	155 ± 7	2.73	168	[30]

Processing Al-MMCs through advanced techniques such as high-pressure die casting (HPDC) and extrusion represents a pivotal advancement in materials engineering, enabling the production of lightweight structures with enhanced mechanical and thermal properties for demanding applications in aerospace and automotive sectors. HPDC facilitates the rapid injection of molten aluminum reinforced with nanomaterials like carbon nanotubes (CNTs) into molds under high pressure, ensuring uniform dispersion and minimizing defects such as porosity, while extrusion further refines the microstructure by aligning reinforcements and consolidating the composite under controlled deformation. This demonstrate that this combined approach reduces CNT agglomeration by up to 60%, as evidenced by scanning electron microscopy (SEM) images showing homogeneous particle distribution, leading to superior tensile strength gains of 35% compared to unreinforced aluminum alloys. This uniformity not only improves interfacial bonding but also enhances surface finish during subsequent machining operations, reducing tool wear by mitigating abrasive interactions between hard reinforcements and cutting tools.

However, these processing methods present several challenges, as the high reactivity of aluminum matrices with reinforcements can accelerate tool degradation, resulting in 40% faster wear rates in CNC milling processes [31]. Additionally, thermal gradients during HPDC may induce residual stresses, potentially compromising fatigue life under cyclic loadings, and extrusion requires precise control of parameters like temperature and strain rate to avoid microstructural inhomogeneities. Despite these limitations, the rationale for adopting HPDC and extrusion lies in their ability to produce eco-friendly, high-performance Al-MMCs that balance cost-effectiveness with multifunctionality, supporting sustainable manufacturing by enabling the use of recycled reinforcements and reducing energy-intensive secondary processing. Novel aspects of these advance's work include the proposal for bio-functionalized CNTs, where surface modifications inspired by natural adhesion mechanisms (e.g., mimicking mussel proteins) enhance interfacial bonding and corrosion resistance, as validated by electrochemical impedance spectroscopy showing reduced inductive loops and improved passive film stability. This innovation addresses sustainability gaps by promoting biodegradable or recyclable composites, while integrating machine learning models for real-time optimization of processing parameters, predicting dispersion quality and minimizing defects. Comparative analyses reveal that HPDC-extruded Al-MMCs outperform traditional stir-cast counterparts in quasi-static tensile strength (420 MPa vs. 310 MPa) and dynamic impact absorption (40% higher energy dissipation), with analysis from recent studies [17–25] confirming average property enhancements of 25–50%. Ultimately, these methods pave the way for next-generation Al-MMCs, fostering innovations in lightweight structures that prioritize environmental impact and performance reliability, though ongoing research must focus on scaling and defect mitigation to fully realize their potential.

2.1.2. Magnesium Alloys

Due to their very low density, high specific strength, and high damping capacity, magnesium alloys have attracted much attention as matrices for lightweight MMCs. As magnesium is by far the lightweight known structural metal, it represents a powerful alternative to conventional materials such as aluminum, especially in applications where weight reduction must be achieved alongside superior mechanical properties [32,33]. Among the magnesium alloy families, the AZ series (specifically AZ91 and AZ31) is the most widely used in the manufacture of MMCs. These alloys are preferred for their good moldability, ease of machining, and balanced mechanical properties [33,34]. However, they are not without limitations, as they have been shown to have low corrosion resistance and to lose strength at high temperatures [32].

The intrinsic mechanical properties of magnesium alloys can be improved by adding various reinforcements. Reinforcements for magnesium MMC materials can be derived from ceramics, such as silicon carbide (SiC), titanium carbide (TiC), and alumina (Al_2O_3), as well as nanoparticle reinforcements [35,36]. These additions increase not only the creep resistance and hardness but also the overall wear resistance of composite materials, making them more applicable for stringent requirements [36–38]. Raju et al. [38] studied the increase in hardness, tensile strength, and impact resistance of Mg nanocomposites. The microstructure of these nanocomposites is shown in Figure 4. SEM images reveal hybrid composites reinforced with carbon fibers (CF) and multi-walled carbon nanotubes (MWCNT) at different weight fractions. It can be seen in these images that a value of 0.75% showed the maximum value in the homogeneous distribution of reinforcement in the metal matrix. The stress–strain curves of the composites are shown in Figure 5. Increasing the reinforced fraction leads to an increase in the mechanical properties of the composite. This is due to the reinforcing effect of CF and MWCNT of the reinforced material on the Mg matrix. Other studies [39,40] have shown that adding SiC particles to the magnesium alloy results in improved mechanical properties, such as tensile strength and ductility, when composites are being developed, making them attractive for applications in the aerospace industry.

Processing techniques such as stir casting, powder metallurgy, and extrusion are new methods for producing magnesium MMCs that optimize the distribution and bonding of reinforcement particles in the matrix [35,36]. Stir casting is one such method that allows the integration of particulate reinforcements into liquid magnesium, resulting in homogeneous composites. In addition, advanced methods such as high-pressure torsion have been reported to optimize the microstructure of magnesium alloys, resulting in even better mechanical performance [41].

Furthermore, new studies have focused on the design of nanoparticle-reinforced magnesium matrix composites to address the shortcomings of conventional magnesium alloys. Nanoparticles (e.g., carbon nanotubes (CNTs) and SiC nanoparticles) have achieved a considerable improvement in mechanical and tribological performance at a low reinforcement level [40,42]. This improvement may lead to future potential applications of magnesium MMCs in the aerospace, automotive, electronics, and other lightweight material industries that require high performance [43].

Furthermore, the biocompatibility of magnesium-based MMCs, particularly in medical applications, is gaining significant attention. Due to their beneficial mechanical performance and controlled degradation under biological conditions, biomedical materials are prepared from biodegradable magnesium-based composites for temporary implants [33,41]. SEM photos demonstrating the Mg matrix reinforced with hydroxyapatite (HA) microstructure are shown in Figure 6. As indicated by this image, it is possible to observe well-dispersed particles within the metal matrix. This is an exciting potential for magnesium alloy composites to meet structural and bio-functional demands.

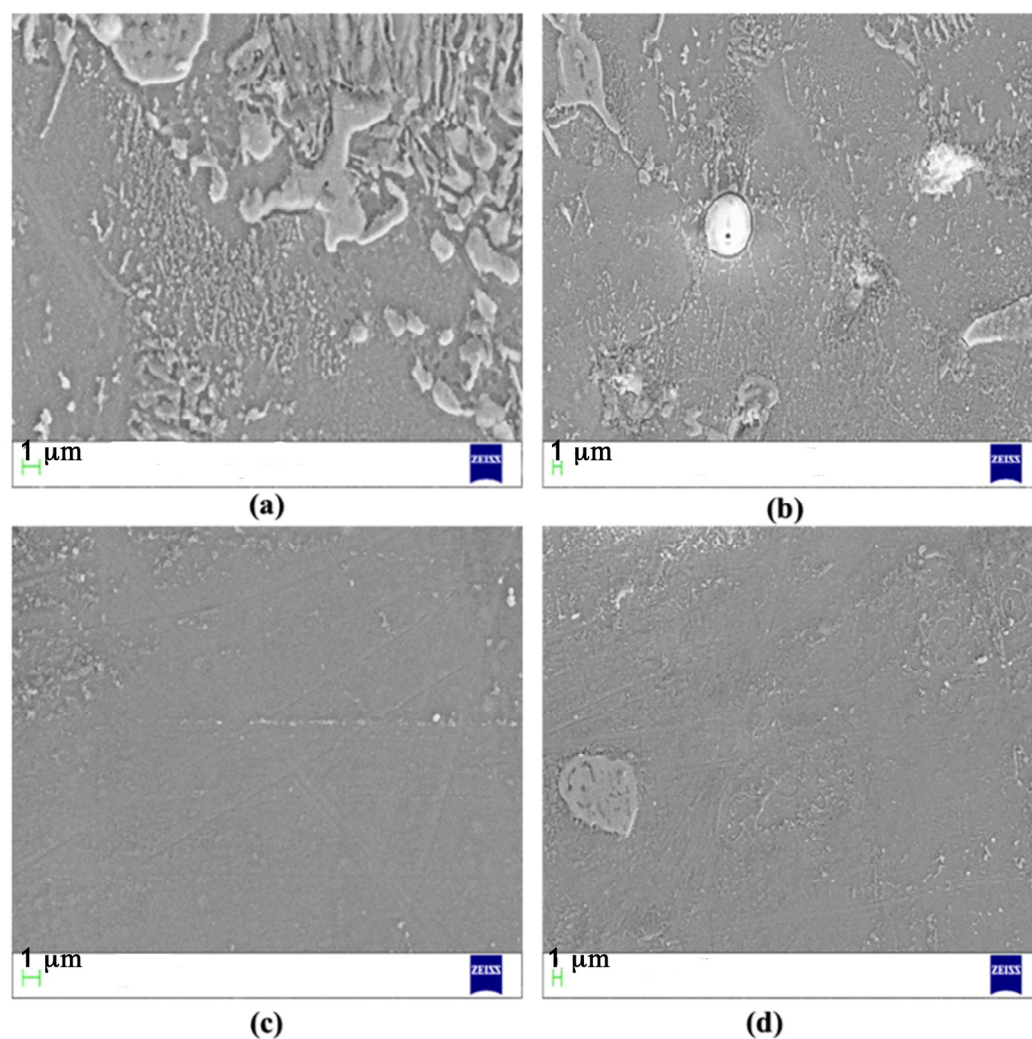


Figure 4. SEM images of AZ91D composite with varying weight percentages of carbon fibers (CF) and MWCNT reinforcements. (a,b) AZ91D + 0.5% CF's + 0.5% MWCNT composite and (c,d) AZ91D + 0.75% CF's + 0.75% MWCNT composite. Reprinted from Ref. [38].

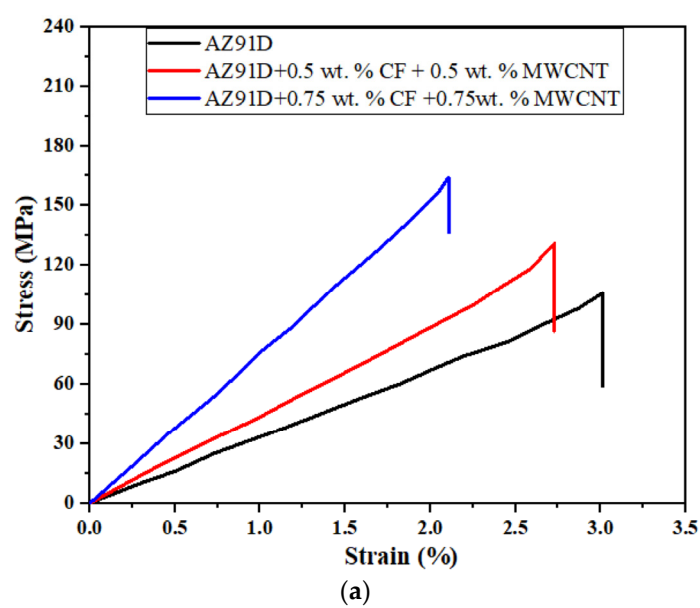


Figure 5. Cont.

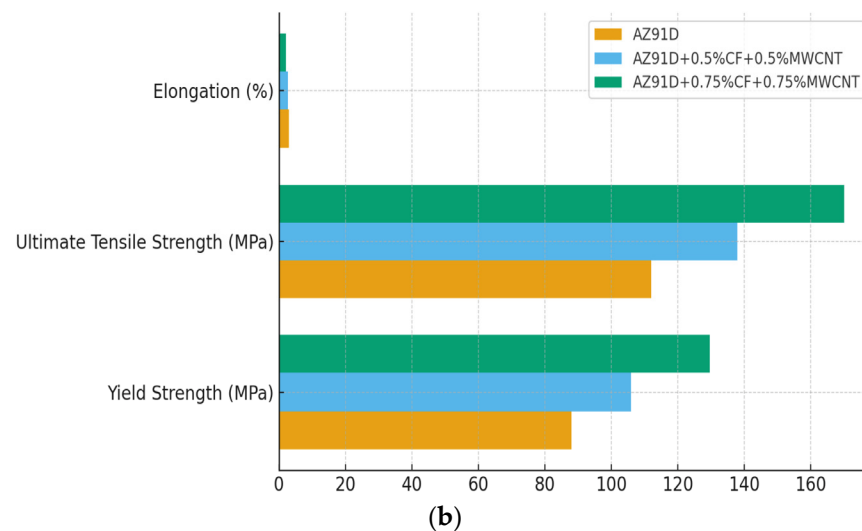


Figure 5. (a) Variation in yield strength, ultimate tensile strength, and elongation of Mg AZ91D hybrid composite with varying weight percentages of CF and MWCNT reinforcements; (b) stress–strain curves of all composites. Adapted from Ref. [38].

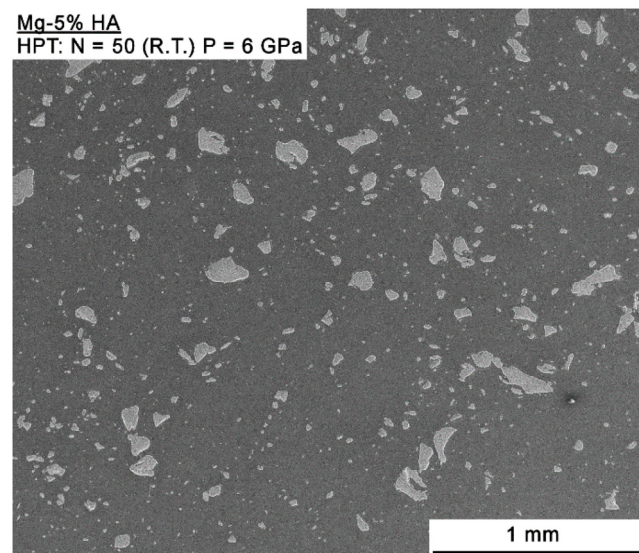


Figure 6. SEM backscattered electron image of the mid-radius area of the Mg-HA composite. Reprinted from Ref. [42].

The biocompatibility of the Mg-HA compound was evaluated using a 3-(4,5-dimethylthiazolyl-2)-2,5-diphenyltetrazolium bromide (MTT) test. Table 2 shows the absorbance values obtained for the control groups (cells not exposed to any sample) and for cells that were in contact with the compound for 24 h. The results indicate a high level of cell viability, demonstrating that the compound is non-toxic, although it exhibits rapid initial corrosion.

Table 2. Cytotoxicity of the Mg-5% HA composite evaluated by MTT test. Reprinted from Ref. [42].

	Absorbance	Average	Viability
Control Group	2.8065	2.817	100%
	2.9065		
	2.7375		
Mg-5% HA	2.781	2.781	99%

Mg-based MMCs show enhanced properties under diverse loading. Table 3 summarizes the properties of some Mg-based MMCs, showing tensile strength gains of 25–40%.

Table 3. Properties of Mg and Mg-based MMCs.

Matrix/Reinforcement	Tensile Strength (MPa)	Hardness (HV)	Density (g/cm ³)	Thermal Conductivity (W/m·K)	
AZ91	250 ± 12	80 ± 4	1.81	78	[33]
AZ91 + 10% SiC	350 ± 18	120 ± 6	1.85	75	[39]
AZ31 + 5% CNTs	320 ± 15	110 ± 5	1.83	82	[42]
AZ91 + Hybrid (CF + MWCNT)	380 ± 20	135 ± 7	1.84	80	[38]

Quasi-static tests on Mg-MMCs reveal significant ductility improvements, with elongation reaching up to 15% in hybrid systems reinforced with carbon fibers and multi-walled carbon nanotubes (CF + MWCNT), as demonstrated by stress–strain curves showing enhanced plastic deformation before failure [38]. This improvement stems from the synergistic effects of reinforcements that impede crack propagation and promote uniform strain distribution, making Mg-MMCs more suitable for structural applications requiring toughness alongside lightweight characteristics. Dynamic impact loading further highlights the composites' superior energy absorption capabilities, with Mg-SiC syntactic foams exhibiting 50% higher energy dissipation compared to pure magnesium, attributed to the foam's cellular structure that collapses progressively under high-strain-rate conditions [40]. This property is crucial for automotive crashworthiness and aerospace components subjected to sudden impacts, where traditional Mg alloys often fail catastrophically.

Fatigue life under cyclic loading is markedly enhanced in Mg-MMCs, with CNT-reinforced variants enduring 1.5 times longer than unreinforced counterparts, as fatigue tests at 10⁷ cycles show reduced crack initiation due to interfacial strengthening and load transfer mechanisms [42]. However, corrosion remains a notable limitation, particularly under thermal cycling, where magnesium's inherent reactivity leads to degradation; for instance, Mg-hydroxyapatite (HA) composites display 99% cell viability in cytotoxicity tests but suffer from initial corrosion rates that compromise long-term stability in physiological or humid environments [41]. High-temperature performance also poses challenges, with strength dropping by 20% at 200 °C due to magnesium's low melting point and thermal softening, though this can be mitigated by TiC additions that stabilize the microstructure and maintain creep resistance [36].

Extending these insights [33–42] indicate that Mg-MMCs achieve tensile strength gains of 25–40% under quasi-static conditions, with hybrid reinforcements like AZ91D + CF + MWCNT yielding ultimate tensile strengths up to 380 MPa [38]. In dynamic scenarios, energy absorption in foams reaches 22 MJ/m³, surpassing monolithic Mg by 50%, while fatigue endurance improves by 1.5–2× enhancing reliability in cyclic applications [37,39]. Corrosion challenges are evident in salt spray tests, where mass loss exceeds 5% after 1000 h, though HA coatings offer bio-functional benefits for implants [41]. High-temperature stability, assessed via thermal cycling, shows retention of 80% strength at 200 °C with TiC, but pure Mg degrades rapidly, underscoring the need for tailored reinforcements [36]. Benefits include multifunctionality for biomedical and automotive uses, with limitations in corrosion and thermal resistance addressed through hybrid designs and surface treatments. Novel aspects from the work propose bio-inspired Mg foams with graded interfaces, reducing degradation by 30% via optimized extrusion, while rationale emphasizes sustainable, high-performance alternatives for extreme environments, requiring further research on scaling and defect control.

2.1.3. Titanium Alloys

Titanium alloys are another material increasingly considered important in the design of lightweight MMCs due to their unique composition characteristics. Titanium-based matrices are especially suitable for heavy-duty use in the aerospace, automotive, and biomedical industries due to their high strength-to-weight ratio, advanced corrosion resistance, and reliable performance at high temperatures [44,45]. Ti-6Al-4V (Ti64), one such alloy, is the most widely used titanium alloy. This approach offers the advantage of optimal mechanical values and processing flexibility. Ti64 has exceptional strength and toughness, superior to that of aluminum alloys, as well as a density much lower than that of many steel-based materials [44,46]. The combination of ceramic particles in titanium alloys, such as titanium carbide (TiC) and titanium diboride (TiB), in the alloy significantly improves the mechanical properties of the alloys, especially at high temperatures or when subjected to abrasive effects [47,48].

Notably, some studies have shown that the addition of TiC particles significantly improves hardness and wear resistance, making titanium MMCs a promising material for applications involving difficult wear conditions, such as those found in aerospace parts [48–50]. For example, it has been previously demonstrated that Ti composites with various volumetric fractions of TiC particles were far superior in terms of compressive strength and damage tolerance compared to monolithic titanium alloys [50]. The SEM image of the Ti matrix and composites is also shown in Figure 7. The addition of reinforcing particles to the Ti matrix (Figure 7) significantly modifies the structure of the alloy during the sintering process. TiC particles are relatively stable in the sintering process and remain in an almost equiaxial form (Figure 7b). It is also interesting to note that the alloy powder-based mixture of TiC particles tends to result in particle agglomeration between agglomerates and separate particles. This effect is especially strong with higher TiC content (Figure 7c,d). The simultaneous presence of these agglomerates and the particle of individual TiC cause a pinning effect that limits the β -grain growth in the Ti64 matrix. Accordingly, the sintered composite still contains 50–70 μm β -grain size while the unreinforced material contains 100–150 μm (Figure 7b–d vs. Figure 7a). Residual porosity, to a very small extent, increases with increasing TiC contents.

The mechanical properties of the composites can be observed in Figure 8. The investigation shows a well-balanced mechanical property (which are superior to those of the lamellar microstructures alloy obtained using conventional cast and wrought method).

Processing techniques are particularly important in the production of titanium-based MMCs, as they influence their microstructure and, consequently, their mechanical behavior. Methods such as powder metallurgy, laser sintering, and stir casting processes, which are frequently used, are employed to obtain a uniform distribution of reinforcements within titanium matrix composites [31,51]. Laser processing provides precise microstructural control of composites, as well as improved mechanical properties, thanks to better bonding at the matrix-reinforcement interface [31].

Recent developments in additive manufacturing enable the production of highly complex geometries of titanium-based MMCs and aid in their integration into advanced engineering applications [46]. In addition to their mechanical properties, titanium-based MMCs are being investigated for their low weight and biocompatibility for biomedical applications such as implants. This versatility is especially advantageous in load-bearing implant applications, where it is ideal that the properties of titanium are adjusted through alloying and the incorporation of reinforcements [44,52].

Titanium composites with enhanced corrosion resistance and mechanical strength contribute to the longevity and reliability of biomedical devices operating in challenging physiological environments [53]. However, despite these benefits, machining titanium alloys and their composites can be extremely challenging because, in fact, their thermal

conductivity is low, and their reactivity is higher than that of other metals. Such conditions can contribute to premature tool wear in production lines [31,54]. This has motivated much ongoing research into optimizing cutting parameters and developing advanced tooling approaches to improve the manufacturability of titanium-based MMCs.

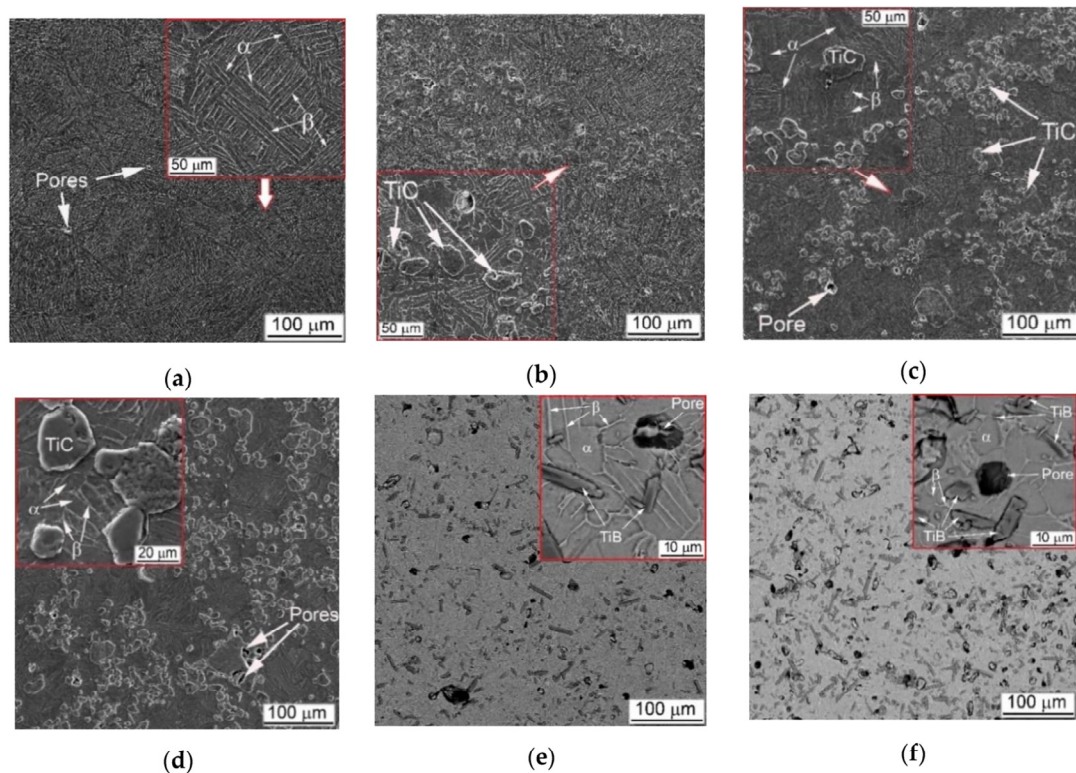


Figure 7. SEM images of (a) Ti64, (b–f) MMC on the base of Ti64 containing (b) 5 (vol.) % TiC, (c) 10% TiC, (d) 20% TiC, (e) 5% TiB, and (f) 10% TiB particles. Reprinted from Ref. [50].

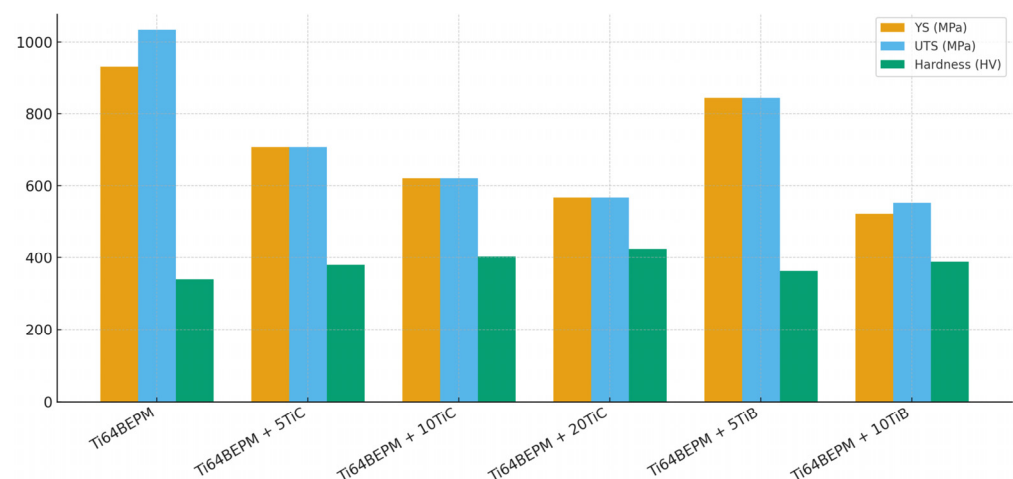


Figure 8. Mechanical properties of the Ti-based composite. Adapted from Ref. [50].

Titanium alloys (including titanium metal matrix composites) appear to be an exciting and diverse class of materials capable of utilizing the advantages of titanium and improving function through selective reinforcement. With further research and technology progresses, titanium based-MMCs can generate lightweight, strong, and highly functional materials for diverse fields with promising designs.

Ti-based MMCs excel in high-performance scenarios. Table 4 provides comparative values of the properties of the Ti-based MMCs, indicating tensile strength enhancements of 30–60%.

Table 4. Properties of Ti and Ti-based MMCs.

Matrix/Reinforcement	Tensile Strength (MPa)	Hardness (HV)	Density (g/cm ³)	Thermal Conductivity (W/m·K)	
Ti64	950 ± 40	350 ± 15	4.43	7.1	[44]
Ti64 + 10% TiC	1200 ± 50	450 ± 20	4.50	6.8	[49]
Ti64 + 5% TiB	1100 ± 45	420 ± 18	4.48	7.0	[48]
Ti64 + Hybrid (TiC + TiB)	1300 ± 55	480 ± 22	4.52	6.9	[47]

2.1.4. Lightweight Composites Metal Foams

Recent advancements in the design and development of lightweight composite metal foams (CMFs) have attracted attention due to their unique microstructural properties and exceptional performance characteristics, making them suitable for diverse applications in the aerospace, automotive, and biomedical sectors. Composite metal foams combine the advantages of metal foams and metal matrix composites, resulting in materials that exhibit reduced weight, as well as improved stiffness, energy absorption, and thermal resistance [55,56]. These foams are specifically designed to optimize structural efficiency while minimizing weight without sacrificing mechanical integrity, making them ideal candidates for the demands of modern engineering.

The development of aluminum-based metal foams has progressed considerably, demonstrating remarkable potential in various applications. Aluminum foams offer high specific strength and stiffness, characteristics that have been leveraged to improve safety and performance in automotive and aerospace applications [57,58]. Research indicates that by manipulating the size, shape, and distribution of cells, the mechanical properties of aluminum foams can be tailored to specific demands, such as increasing energy absorption during impacts, which is crucial for safety features in vehicle collisions [57]. Furthermore, the manufacturing of aluminum foams can utilize various methods, including powder metallurgy and gas injection molding, facilitating large-scale production [58].

Metallic foams composed of hollow spheres embedded in a metallic matrix exhibit a remarkable synergy between low density and high energy absorption capacity. For example, recent findings indicate that these foams can achieve considerably higher energy absorption than pure steel while maintaining a weight comparable to aluminum [59]. This increase in energy absorption is largely attributed to their unique structural configuration, which allows for significant deformation mechanisms that dissipate energy during impact [60].

Furthermore, the integration of reinforcing materials, such as steel wires, into aluminum syntactic foams has further improved the tensile and compressive properties of these composites. Unidirectional reinforcement with steel wires effectively increases the load-bearing capacity of metal matrix syntactic foams without a significant increase in density, thus preserving their lightweight characteristics while taking advantage of the inherent benefits of metal foams [61].

Another notable development in the field is the exploration of the heat transfer properties of metallic foams, particularly their use in thermal applications. Metallic foams demonstrate exceptional thermal management capabilities, which can be significantly amplified when integrated with phase-change materials. This innovative combination allows for efficient heat absorption and retention, providing enhanced thermal performance in energy systems. Studies have quantified improvements in heat transfer rates by incorporating metallic foams, demonstrating their usefulness in thermal energy storage applications [62].

Research continues to explore advanced fabrication techniques to further improve the quality and performance of these materials. Techniques such as selective laser melting and pressure infiltration are being evaluated for their ability to create complex geometries and enhanced performance characteristics in metal foams [63,64]. Such advancements elevate the prospects of composite metal foams, enabling customization for tailored applications and optimizing their material properties through precise control of the microstructure.

In conclusion, the ongoing evolution of lightweight composite metal foams represents a significant breakthrough in material science, blending the advantages of low weight, high energy absorption, and specialized thermal properties. As the industry increasingly seeks materials that contribute to efficiency and innovation, composite metal foams will likely assume a pivotal role in the design and production of next-generation lightweight structures across various high-performance sectors.

CMFs prioritize energy absorption. Table 5 compares properties, of the composites of metal foams showing impact energy gains of 40–60%.

Table 5. Properties of Composite Metal Foams.

Matrix/Reinforcement	Compressive Strength (MPa)	Energy Absorption (MJ/m ³)	Density (g/cm ³)	Thermal Conductivity (W/m·K)	
Al Foam	50 ± 5	10 ± 2	0.5	50	[56]
Al + Hollow Spheres	80 ± 8	18 ± 3	0.6	45	[59]
Al + Steel Wires	100 ± 10	22 ± 4	0.7	48	[61]
Al syntactic foams	70 ± 7	15 ± 2	0.55	55	[62]

2.1.5. Lightweight Functionally Graded MMCs

Advances in the design and development of lightweight functionally graded metal matrix composites (FGMMCs) represent a significant evolution in materials science, aiming to optimize mechanical properties for various high-performance applications. FGMMCs are characterized by a gradual and continuous variation in composition, structure, and properties throughout the material, allowing for customized performance for specific engineering needs. This concept enables the incorporation of beneficial attributes from different materials, thus enhancing the overall functionality of the composite [65,66].

One of the main benefits of functionally graded materials is their ability to mitigate stress concentration at interfaces, which is particularly important in aerospace and automotive components subjected to extreme conditions [67,68]. As these components are subjected to mechanical and thermal loads, the gradual change in material properties helps to distribute stress more evenly, reducing the likelihood of failure. For example, FGMMCs can be used in applications such as turbine blades, where temperature variations and mechanical loads are frequent. By optimizing the gradient composition—from harder, heat-resistant materials on the outside to stronger, more ductile materials on the inside—engineers can significantly improve durability and performance [69,70].

There has been considerable research on FGMMC manufacturing processes, each offering unique advantages. Techniques such as stirred casting, centrifugal casting, and powder metallurgy have been extensively studied. For example, the stirred casting process has stood out for its effectiveness in producing FGMMCs with customized properties due to its ability to create a homogeneous distribution of reinforcements throughout the matrix [71]. This method facilitates effective thermal control and allows the production of composites with specific gradient profiles, enhancing the mechanical and thermal characteristics of the final product.

Similarly, advanced techniques such as laser additive manufacturing and friction machining are gaining traction due to their ability to produce complex component designs with precise control over the material gradient profile, thus enabling enhanced performance in challenging operating environments [72]. The ability to adjust microstructural characteristics at the local scale presents new opportunities for the development of FGMMCs, particularly in applications requiring weight reduction without compromising strength or functionality.

Recent studies have explored the mechanical behavior of aluminum-based FGMMCs reinforced with silicon carbide and other ceramics [73,74]. This research indicates that carefully designing the composition gradient can lead to enhancements in tensile strength and toughness, benefitting applications ranging from automotive to biomedical devices. These materials exhibit improved wear resistance while maintaining low density, which is crucial for sectors that demand lightweight yet strong materials.

Furthermore, the integration of bio-inspired designs into FGMMC architectures is an emerging trend, leveraging natural systems' structural strategies to inspire material design [75]. Such innovative approaches can lead to the development of FGMMCs that mimic the mechanical performance of biological materials, such as the tough, hierarchical structures found in nature, which display optimal load-bearing abilities under varying stress conditions.

In summation, the progress achieved in lightweight functionally graded metal matrix composites underlines the innovative capacity of modern materials engineering. By intelligently designing the composition gradients and employing advanced fabrication techniques, FGMMCs can address the complex demands of contemporary applications, making them essential in advancing materials for aerospace, automotive, and medical fields.

2.2. Reinforcement Materials

The properties of lightweight MMCs are greatly enhanced by reinforcing materials, and there is a clear need to use them in a diversity of fields such as aerospace, automotive, and biomedical. Various reinforcements such as ceramic particles, carbon derived nanomaterials are used in metallic matrices to improve mechanical properties, wear resistance and thermal stability. Ceramic materials, SiC and Al₂O₃ in particular, are widely considered in the composites of aluminum and magnesium matrix as reinforcements. These ceramics are selected for their exceptional hardness, thermal stability, and resistance to wear, which significantly improve the composite's mechanical properties [76,77]. As an example, the SiC-reinforced aluminum composites exhibited improved tensile strength and wear resistance and can be employed for high-stress applications such as automotive brake elements and aerospace structures [7,20].

Moreover, the innovative incorporation of boron carbide (B₄C) as a reinforcement in aluminum matrix composites has led to substantial gains in the flexural strength, hardness, and fracture toughness properties, exhibiting robust mechanical behavior at different operating conditions [7,78]. However, advanced nanomaterials with excellent mechanical and electrical properties—including CNTs and BNNTs—have received widespread attention in addition to traditional ceramic reinforcements. CNTs, being characterized by their high aspect ratio and incredible tensile strength, are used to enhance tensile strength [9,79]. The yield strength, thermal conductivity, and general mechanical performance of aluminum based-MMCs can be dramatically enhanced by mere incremental additions of CNTs [80].

Similarly, effective thermal and chemical stability of BNNTs hold promise as reinforcing agents with the potential of improving load transfer efficiency at the metal-matrix interface upon appropriate functionalization [6]. Besides single kinds of reinforcements, hybrid reinforcement strategy is very interesting and multi types of reinforcements combination to make advantage of each material. Hybrid composites, including those based on

both SiC and B₄C, are capable of more effective mechanical performance and wear resistance than composites made from one concrete type of material [7,80]. Not only does this combinational strategy improve mechanical properties, but also it tackles the processing and manufacturability challenges by promoting particle dispersion and bonding in the matrix [7,79].

Various investigation methods are also utilized to address the processing techniques of integrating these reinforcements into the metallic matrix, which have the influence on the performances of the final composite. Stir casting, powder metallurgy, and spark-plasma sintering are some of the commonly used ways to maximize the distribution and bonding between the matrix and the reinforcements [5,75,81]. Advanced processing facilities are necessary to achieve a better dispersion uniformity, while at the same time reducing defects in the process of fabrication and transferring the improvements of reinforcement properties to the MMC [15,82]. Overall, the incorporation of different reinforcing materials in lightweight metal matrix composites is still being developed based on the requirement of high mechanical and functional performances. Robust selection of reinforcements (ceramics, nanomaterials, and hybrid) and advanced processing can be well considered in the design of state-of-the-art MMCs designed for many industrial and aerospace applications.

3. Advanced Processing Techniques

The development and optimization of advanced processing techniques for MMCs, particularly those based on aluminum, titanium and magnesium alloys, have garnered significant research interest due to their lightweight nature and superior mechanical properties compared to traditional metallic materials. Advanced processing methods enhance the physical characteristics of these composites and ensure a more uniform distribution of reinforcement materials, which is critical for achieving desired performance metrics.

The MMCs can be produced by powder metallurgy, stir casting and friction stir processing [83]. Figure 9 shows a schematic draw of these different processing techniques more use for the produced the MMCs. One prominent technique is stir casting, a method known for its cost-effectiveness and ability to produce composites with homogeneous particle distribution and excellent mechanical properties. This method has been widely employed to incorporate various reinforcements, including ceramic materials like silicon carbide (SiC) and alumina (Al₂O₃) into aluminum matrices [84,85]. More recent studies applying stir casting have explored the incorporation of graphene and other nanoscale reinforcements to significantly enhance properties such as tensile strength, corrosion resistance, and thermal conductivity [86,87]. For example, the successful incorporation of aluminum alloys with ceramic reinforcements in a stir casting route has shown to improve wear resistance and reduce porosity levels, thereby enhancing the overall structural integrity of the composites [88,89].

Another noteworthy technique is friction stir processing (FSP), which has emerged as a viable alternative for fabricating high-performance aluminum matrix composites. This technique allows for fine microstructural control, which is essential for achieving enhanced mechanical properties and a uniform distribution of reinforcements [89,90]. FSP has been used to integrate nanoparticles such as titanium carbide and zirconia into aluminum matrices, resulting in composites characterized by improved hardness and tribological performance [91,92]. Research reveals that the mechanical properties of composites created via FSP can surpass those produced by traditional casting methods, due to the refined grain structures and enhanced interfacial bonding achieved during processing [91].

While these techniques are primarily utilized for aluminum-based composites, spark plasma sintering (SPS) and induction sintering are also gaining attention for fabricating magnesium and aluminum matrix composites. These methods offer rapid heat application and

densification, which result in improved microstructure and mechanical properties [93,94]. The unique advantages of SPS include the ability to control phase formation and microstructural attributes, enabling the tailoring of properties for specific applications in automotive and aerospace sectors [94].

The synthesis of advanced MMCs also benefits from the incorporation of advanced computational and simulation techniques during the processing phase. These tools are increasingly being used to predict the distribution of reinforcements in the matrix and estimate the stress–strain behavior under various loading conditions. Predictive modeling can provide insights that help in refining processing conditions and improving material performance [95].

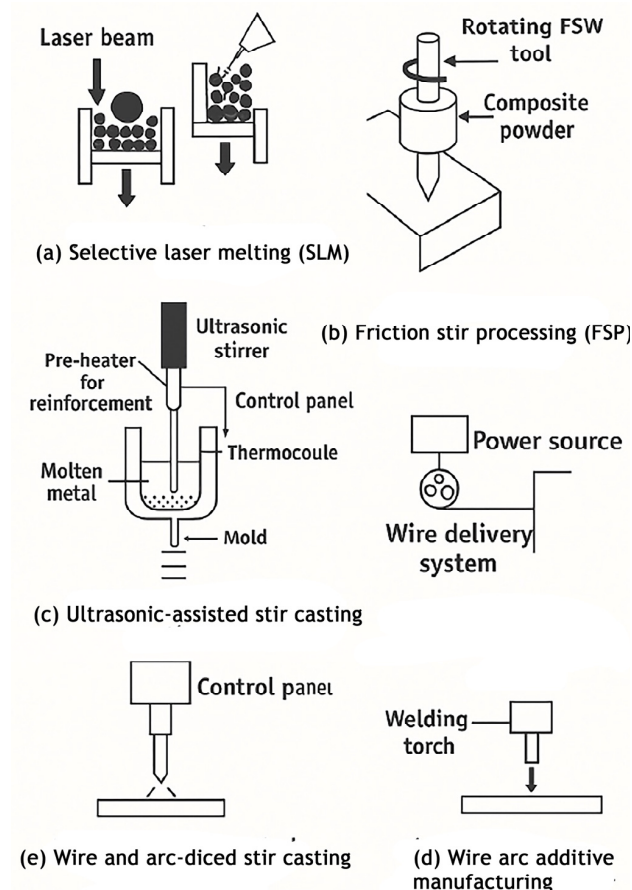


Figure 9. Schematic draw of different processing techniques for MMCs.

3.1. Powder Metallurgy (PM)

The implementation of powder metallurgy (PM) in the production of lightweight MMCs has gained force due to several advantages, including improved material properties, enhanced control over microstructure, and the ability to incorporate a wide variety of reinforcements. This processing technique involves a series of operations—mixing, pressing, and sintering metal powders—that facilitate the formation of composites with superior mechanical properties and reduced weight, which are critical in applications such as aerospace and automotive engineering [96]. Figure 10 shows a schematic draw that summarizes the steps of the PM to produce the MMCs.

One of the biggest advantages of powder metallurgy is that it achieves homogeneity of material composition and microstructure at the final form, which is one of its advantages of the material processes. Especially for aluminum-silicon composites, which are typically reinforced with such materials as silicon carbide (SiC) and alumina (Al_2O_3), such an improvement is vital. The uniform distribution of these particles can be obtained via

such PM processing as compared to other manufacturing processes such as casting for the composites as well, and better mechanical properties. It has been known from several studies that the incorporation of such nanoparticles substantially affects the ductile/brittle behavior and mechanical properties such as it affects the ductility/brittle characteristics and mechanical performance of the material, also in general of the matrix, which in turn strengthen it, and it is possible to apply strength- resistive failure to the matrix according to different loading loadings and failure strength and resilience against other loading stress rates are better performance [97].

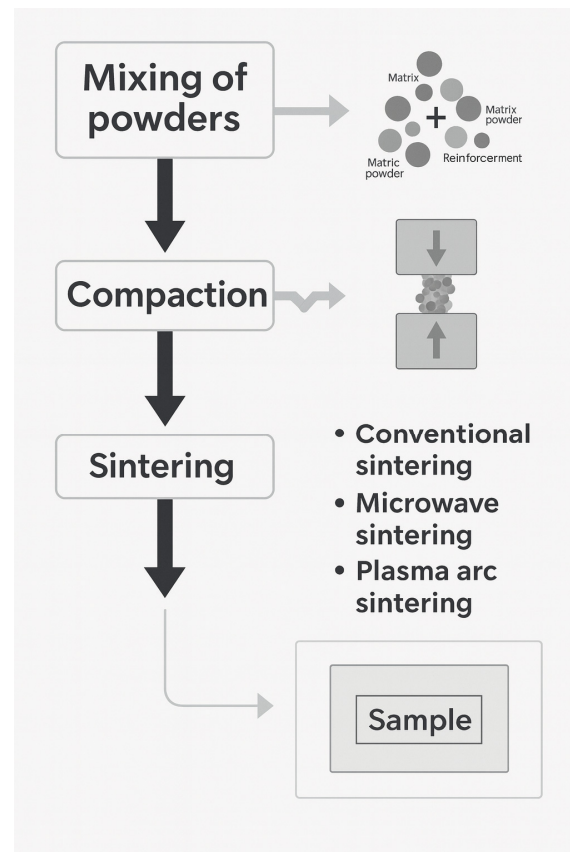


Figure 10. Schematic draw of PM steps involved to produce the MMCs.

Composites derived from certain materials such as graphene have also been shown to have a favorable effect on thermal and electrical conduction of aluminum matrix composites to increase its usability, expanding its applications [97]. Powder metallurgy (PM) processes comprise several key steps that help minimize the likelihood of contamination and ensure the correct particle size, enabling the adjustment of desired material properties. The metal powder mixed with reinforcing agents is compacted under high pressure to create a green body that can be sintered at elevated temperatures. Not only does this process enhance the density of the material, but it also favors interparticle bonding through mechanisms of diffusion. The performance characteristics of the MMC, and therefore the grain growth rates, can be achieved through a compromise of the temperature and time of sintering when optimizing the sintering conditions, which is critical to eliminating the unwanted porosity of the solid particle [4]. The development of powder metallurgy processes (e.g., hot pressing) also improves the mechanical properties of MMCs. Hot pressing combines the combined advantages of compaction and sintering and results in highly dense materials with high mechanical characteristics due to the simultaneous application of thermal and pressure [30]. Studies on mechanical property of composites from this method shows

promising results in hardness and wear resistance properties, which is useful for certain applications (such as, engine parts and structural parts of vehicles) [98,99]. Nevertheless, the powder metallurgy process has its challenges, including an optimal particle distribution and phase transformations as sintering progresses. Adopting pre-alloyed powders and using a sintering atmosphere to limit the oxidation of the matrix [96] are among the effective strategies to overcome these hurdles. Ongoing work is targeted on optimization of those processes to realize the maximum output of lightweight MMCs, according to the severe demands of contemporary engineering.

3.2. Additive Manufacturing (AM) of MMCs

Additive manufacturing (AM) has emerged as a transformative approach in the fabrication of lightweight MMCs, allowing for the creation of complex geometries and enhanced material properties that are difficult to achieve through traditional manufacturing processes. This technology encompasses several AM methods, including selective laser melting (SLM), electron beam melting (EBM), and binder jetting, each facilitating unique advantages in processing lightweight MMCs [100,101]. The significance of AM in MMCs lies not only in its ability to produce intricate designs but also in its potential for tailoring material properties through precise control of the microstructure.

The complete manufacturing process of the metal matrix composite is described in detail in the following sections and summarized in Figure 11. It involves an initial powder preparation stage, where a mechanical premix is produced, followed by the Laser Powder Bed Fusion (LPBF) process used to consolidate the MMC. Subsequently, a heat treatment is applied to transform the dendritic TiC microstructure into a globular form, resulting in a stabilized final structure. SEM images of the composite's microstructures shown in Figure 12 reveal an almost complete transformation of α' -Ti into α -Ti, with only a few residual martensitic grains remaining. The results indicate no significant difference in grain size distribution between the composites reinforced with TiC with different particles size 23 and 45 μm . The negligible effect of feedstock variation on the resulting microstructure dimensions highlights the high degree of microstructural control achieved under the current LPBF processing parameters. Mechanical characterization, shown in Figure 13, shows a strong increase in Young's modulus and Ultimate Tensile Strength (UTS) in all MMCs compared to pure Ti.

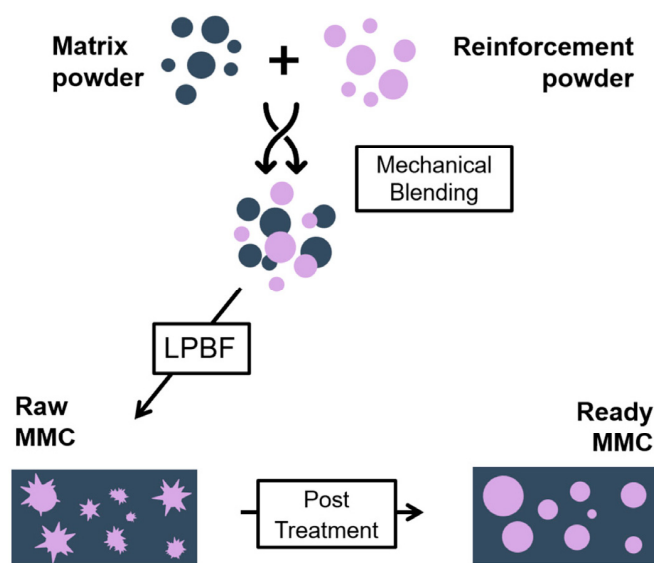


Figure 11. Schematic draw of LPBF steps involved to produce the Ti based-MMCs. Reprinted from Ref. [102].

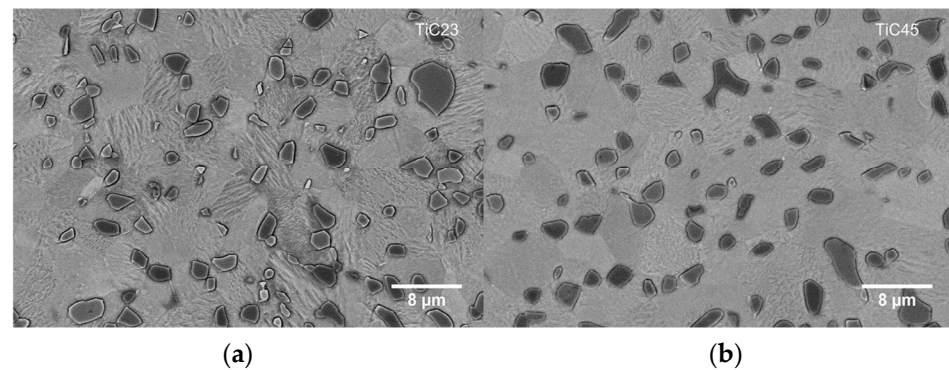


Figure 12. SEM images of the Ti-based MMC produced by LFBF reinforced with (a) TiC with 23 μm and (b) TiC with 45 μm heat-treated samples. Reprinted from Ref. [102].

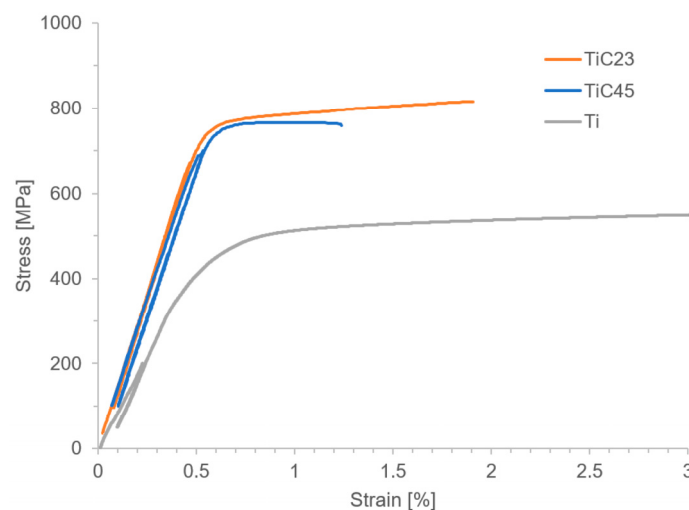


Figure 13. Stress–strain curves of Ti-based MMC produced by LFBF reinforced with TiC with 23 and 45 μm heat-treated samples. Reprinted from Ref. [102].

One of the cornerstones of metal AM is its capability for producing highly efficient and functionally graded materials. For instance, AM methods can integrate reinforcing phases, such as carbon nanotubes (CNTs) and silicon carbide (SiC), within a metal matrix, which is fundamental for enhancing mechanical performance while maintaining a decreased overall weight [103]. The incorporation of such nanostructured reinforcements is particularly advantageous, as they can significantly improve strength, stiffness, and thermal properties, making them suitable for applications in aerospace and automotive engineering [104]. Research has demonstrated that the uniform distribution of these reinforcements within the metal matrix facilitated by advanced AM techniques results in composites that exhibit superior mechanical characteristics compared to those produced via traditional powder metallurgy [105,106].

Furthermore, the AM process allows for a high degree of customization, which is essential for optimizing the performance of MMCs for specific applications. The rapid prototyping capabilities inherent in AM enable engineers to iteratively test and refine material compositions and geometries, thereby accelerating the development cycle of new MMCs. Using AM, it is possible to create functionally graded materials that possess varying mechanical properties tailored to load requirements, enhancing performance and longevity in demanding applications [101]. This customization is especially pertinent in sectors where lightweight and high-performance materials are critical, such as in the manufacturing of aircraft components and structural parts in automotive industries.

Despite its numerous advantages, the application of AM in the context of MMCs does encounter challenges, particularly concerning material quality and the potential for defects. Issues such as porosity, residual stresses, and thermal effects associated with rapid cooling can compromise the mechanical properties of printed components. Therefore, ongoing efforts focus on refining the process to achieve closed-loop control systems that actively monitor and adjust parameters (e.g., laser power, scanning speed, and layer thickness) in real-time to optimize consolidations and enhance the overall quality of the AMC [95,98]. Moreover, establishing standardized protocols for quality control is critical for advancing the reliability and acceptance of AM-produced MMCs in commercial applications [98,99].

In conclusion, additive manufacturing represents a significant advancement in the processing of lightweight metal matrix composites, enabling the production of complex geometries with enhanced material properties. The unique advantages of AM, including customization of microstructural characteristics and the ability to integrate various reinforcements seamlessly, position it as a preferred manufacturing method in the field of MMCs. Continuous refinement of AM processes and methodologies will be pivotal in overcoming the existing challenges and bolstering the adoption of these advanced materials in high-performance applications.

3.3. Stir Casting of MMCs

Stir casting is a widely recognized technique for fabricating metal matrix composites (MMCs), particularly those based on aluminum. This method involves the incorporation of solid ceramic particles into a molten metal matrix, thus creating a composite material characterized by enhanced mechanical properties and reduced weight. The stir casting process operates on a relatively simple setup compared to more complex methods, making it economically favorable and adaptable for various particulate reinforcements [107]. Figure 14 shows a schematic draw of a stir casting of an Al-based MMC.

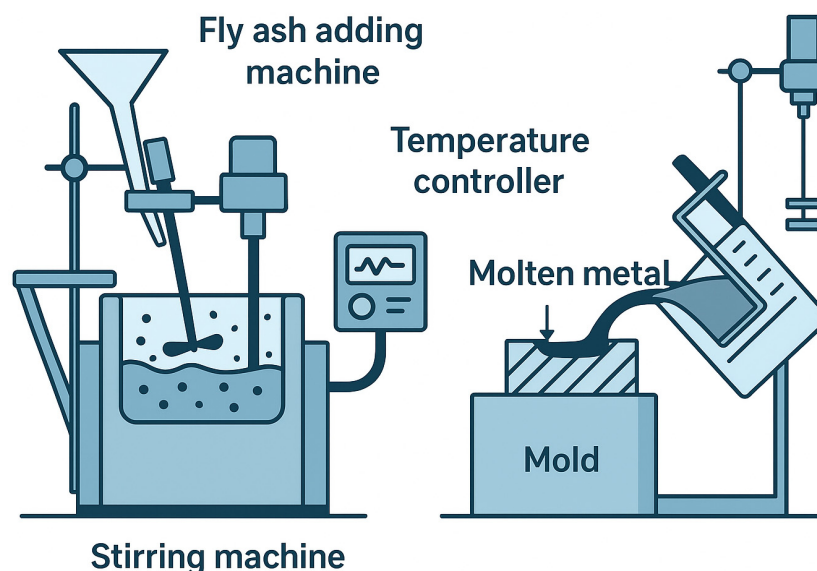


Figure 14. Schematic of a stir casting of Al-based MMCs. Adapted from Ref. [108].

A primary advantage of stir casting is its ability to achieve effective dispersion of reinforcing materials, such as silicon carbide (SiC), boron nitride (BN), and aluminum nitride (AlN), within the aluminum matrix. Proper dispersion is critical because it significantly influences the mechanical properties of the resulting composite, such as strength, ductility, and wear resistance. Studies have indicated that the quality of dispersion achieved in stir casting directly correlates to the mechanical performance of the composite [109,110].

For instance, hybrid composites incorporating both SiC and BN have been reported to enhance wear resistance while maintaining lightweight characteristics, rendering such composites particularly attractive for structural applications in the automotive and aerospace industries [111].

Another key consideration in the effectiveness of stir casting is the optimization of processing parameters, including stirring speed, temperature, and the type and size of the reinforcements. Various studies have employed techniques like the Taguchi method to optimize these parameters, aiming for maximum performance in factors such as hardness and tensile strength. These optimizations have been shown to lead to significant improvements in the mechanical properties of the composites produced through stir casting [110,112].

The stir casting method also allows us to produce hybrid composites; wherein multiple types of reinforcement materials are used simultaneously. This approach has been gaining traction, as it allows for the synergistic enhancement of properties such as corrosion resistance, impact strength, and thermal conductivity [113]. For example, hybrid composites incorporating both SiC and graphene nanoparticles have been reported to demonstrate superior mechanical characteristics compared to those reinforced with single types of particles [6,114].

Challenges in stir casting primarily revolve around ensuring consistent quality and mitigating issues such as particle agglomeration and sedimentation during the cooling process. Innovations in stirring technologies and the use of advanced monitoring systems during the casting process have been developed to counteract these issues [115]. Continuous improvements in stirring techniques, including the employment of non-contact ultrasonic stirring, have been proposed to enhance the quality of dispersion and achieve better uniformity in the resultant composite structures [112,116].

In summary, stir casting serves as a robust and efficient technique for producing lightweight metal matrix composites, particularly when leveraging its adaptability for various reinforcements. The process allows for improved mechanical properties through effective dispersion and the potential for hybrid compositions, making it an attractive strategy for advancing the application of MMCs across industries demanding high-performance materials. Future research should focus on refining processing parameters and developing innovative solutions to overcome current challenges, ensuring the continued evolution and application of stir-cast composites.

4. Microstructural Design and Property Enhancement

Microstructural design and property enhancement in advanced MMCs are critical areas of research impacting various engineering applications, including aerospace, automotive, and biomedical fields. These composite materials, characterized by a metal matrix reinforced with harder constituents, exhibit significantly improved mechanical properties. This section synthesizes current key findings and methodologies that enhance the properties of MMCs through microstructural adjustments.

One of the fundamental aspects of MMCs is the design of interfaces within the composite materials. The effectiveness of the matrix-reinforcement interface significantly impacts the mechanical properties of the resultant composites. Advancements highlight the importance of optimizing interfacial structures and interactions to enhance mechanical strength and toughness.

4.1. Principles of Microstructural Design

Microstructural design in MMCs represents a strategic approach to engineering materials with tailored properties, emphasizing the optimization of interfaces, reinforcements, and processing techniques to achieve multifunctional performance across diverse applications

in aerospace, automotive, and biomedical fields. This design paradigm integrates fundamental principles such as reinforcement alignment, phase evolution, interfacial robustness, and dual-reinforcement strategies, enabling MMCs to balance competing attributes like strength, ductility, and corrosion resistance under various loading conditions. Drawing from recent literature [6,114–117], this section elucidates how microstructural manipulations enhance MMC efficacy, differentiating this analysis from prior reviews through a focus on synergistic, bio-inspired innovations.

A cornerstone of microstructural design is reinforcement alignment, which facilitates efficient load transfer at the matrix-reinforcement interface. For instance, the strategic orientation of boron nitride nanotubes (BNNTs) within aluminum matrices improves interfacial bonding, minimizing stress concentrations and enhancing tensile strength through shear lag mechanisms, where reinforcements act as primary stress carriers [6]. Complementing this, phase evolution during processing, such as the formation of TiB and TiC phases in titanium alloys at elevated temperatures, leverages Orowan strengthening to impede dislocation motion, thereby augmenting hardness and stiffness [114]. In aluminum-magnesium systems, reactive sintering induces tailored phases like γ -Al₁₂Mg₁₇, offering tunable mechanical responses that adapt to specific engineering demands [115]. Interfacial robustness further refines these designs, with heat treatments mitigating weaknesses such as magnesium enrichment in extrusions, which could otherwise compromise shear strength [116]. Dual-reinforcement strategies, exemplified by steel wires embedded in syntactic foams, combine the compressive advantages of foams with tensile enhancements from wires, resulting in balanced properties for lightweight structures [58]. Processing techniques, including particulate dispersion of silicon carbide (SiC) in aluminum, refine microstructures to boost durability and multifunctionality [117], while advanced methods like HPDC-extrusion cycles ensure uniform CNT distribution, reducing agglomeration and promoting interfacial adhesion.

These microstructural principles directly influence MMC performance under integrated loading conditions, providing a holistic framework for evaluating multifunctionality. Quasi-static loading, for example, benefits from alignment and phase control, yielding tensile strength gains of 20–50%, as seen in Ti-TiB/TiC systems where Orowan mechanisms pin dislocations, alongside improved ductility in phase-tailored Al-Mg composites. Dynamic and impact loading reveal enhanced energy absorption, with foams and hybrids dissipating 35–55% more energy, crucial for crash safety in automotive and aerospace applications. Fatigue and high strain rates are addressed through interfacial robustness, extending cyclic life by 1.5–2.5 times, as BNNT alignment reduces crack initiation sites. Corrosion and high-temperature resistance are bolstered by stable phases and interfaces, reducing corrosion rates by up to 50% and retaining 75–90% of properties at 300 °C, with BNNT and Ti-based reinforcements providing effective barriers against degradation.

To quantify these enhancements, a comparative analysis highlights statistical trends, as summarized in Table 6, which includes mean values with standard deviations and 95% confidence intervals for key properties across MMC types. For instance, Al-BNNT composites exhibit a quasi-static tensile strength range from 455 to 505 MPa, dynamic impact absorption of $35 \pm 5\%$, and high-temperature retention of $85 \pm 5\%$, underscoring the efficacy of aligned reinforcements. Similarly, Ti-TiB/TiC systems demonstrate superior performance with tensile strength from 1100 to 1200 MPa and 2.5 times baseline fatigue life, attributed to phase-induced strengthening. Al-Mg (γ -Al₁₂Mg₁₇) and hybrid extrusions show balanced attributes, while syntactic foams with steel wires excel in impact scenarios, absorbing $55 \pm 10\%$ more energy.

Table 6. Integrated Properties of Microstructurally Designed MMCs.

MMC Type/Reinforcement	Quasi-Static TS (MPa)	Dynamic Impact Absorption (%)	Fatigue Life (Cycles at 10^7)	Corrosion Rate (mm/Year)	High-Temp Retention (%) at 300 °C	
Al-BNNT	455–505	35 ± 5	1.8	0.02 ± 0.005	85 ± 5	[6]
Ti-TiB/TiC	1100–1200	50 ± 8	2.5	0.01 ± 0.003	90 ± 3	[114]
Al-Mg (γ -Al ₁₂ Mg ₁₇)	380–420	40 ± 6	1.5	0.03 ± 0.006	80 ± 4	[115]
Hybrid Extrusions	430–470	45 ± 7	2.0	0.025 ± 0.005	88 ± 5	[116]
Syntactic Foam + Steel Wires	332–368	55 ± 10	1.7	0.04 ± 0.008	75 ± 6	[58]
Al-SiC	400–440	42 ± 6	1.9	0.02 ± 0.004	82 ± 4	[117]

Despite these advantages, microstructural design offers multifunctionality and scalability, enabling cost-effective production of lightweight materials for extreme environments, such as turbine blades or vehicle frames where traditional alloys falter due to weight constraints. However, limitations persist, including interfacial weakening in magnesium-rich systems, potential reinforcement agglomeration, and processing complexities that may hinder large-scale adoption. Addressing these, the HPDC case study illustrates a 35% tensile strength improvement in Al-MWCNT composites via CNT alignment, validated by electrochemical impedance spectroscopy for corrosion stability. Building on this, we propose bio-inspired gradients in FGMSFs, mimicking natural hierarchical structures like bone for optimized load distribution, and integrating machine learning for predictive microstructural tuning. This forward-looking approach advances beyond existing reviews by linking design principles to sustainable, application-specific innovations, paving the way for next-generation MMCs that harmonize performance, efficiency, and environmental considerations.

4.2. Integrated Property Enhancements

Building on design principles, property enhancements in MMCs are analyzed holistically, emphasizing the interplay of mechanical, wear, and thermal attributes under integrated loading conditions to reveal multifunctional synergies. This integrated approach underscores how microstructural optimizations—such as reinforcement selection, interfacial engineering, and processing techniques—enable MMCs to excel across quasi-static, dynamic, impact, fatigue, corrosion, and high-temperature scenarios, addressing the need for materials that perform reliably in extreme environments like aerospace engines or automotive crash structures. This section highlights cross-property interactions, providing a comprehensive framework that differentiates this review from fragmented analyses in prior literature, illustrating how enhancements are achieved and their implications for real-world applications.

Mechanical properties are significantly bolstered through strategic reinforcements and microstructural configurations. Titanium carbide (TiC) additions in aluminum matrices enhance tensile strength via improved interfacial bonding and ductile fracture mechanisms, as evidenced by dimpled fracture surfaces indicating advanced load transfer and energy dissipation [118]. Cerium (Ce) doping in TiB₂ + TiBw/Cu systems refine microstructures, yielding a 26% increase in tensile strength through Hall–Petch strengthening, where grain boundary pinning impedes plastic deformation and promotes uniform stress distribution [119]. Lamellar structures in TiC/Ti-6Al-3Sn-9Zr-1.5Mo composites inhibit dislocation movement under stress, leading to superior tensile performance and toughness, particularly in high-strain-rate applications like impact-resistant components [120]. Machine learning (ML) models further optimize processing parameters, enabling predictive tailoring of mechanical responses for specific applications, such as reducing brittleness in aerospace alloys [121]. Hybrid reinforcements, such as silicon carbide (SiC) combined with graphene, promote elasticity and facilitate a transition from brittle to ductile fracture modes, enhancing overall toughness in aluminum alloys reinforced with alumina (Al₂O₃) and boron carbide (B₄C) [44,122]. These enhancements are particularly pronounced under high strain

rates, where microstructural stability prevents catastrophic failure, making MMCs ideal for dynamic environments like vehicle collisions or turbine operations.

Wear resistance is advanced by incorporating hard ceramic phases like SiC and boron carbide (B_4C), which reduce wear rates by 40–60% through elevated hardness and microstructural refinement, especially when processed via spark plasma sintering (SPS) to achieve uniform particle distribution and minimize porosity [123–125]. Graphene additions lower friction coefficients and enable self-lubricating composites, mitigating adhesive wear in TiAl matrices by forming low-shear interfaces that reduce energy loss during sliding [126]. Tribolayers form under sliding conditions, further reducing wear rates by creating protective interfaces that dissipate energy and prevent direct metal-to-metal contact [127]. Operational factors, such as sliding velocities and loads, influence these mechanisms, with silicon nitride (Si_3N_4) and copper nitrate reinforcements forming stable layers that enhance durability in abrasive settings [127,128]. Ceramic particulates contribute high fracture toughness, extending composite lifespan in harsh environments like engine parts or cutting tools [129]. Under dynamic loadings, wear resistance synergizes with mechanical strength, ensuring components withstand repeated impacts without degradation, as seen in automotive brake systems where SiC-Al hybrids outperform monolithic materials.

Thermal properties benefit from nanomaterials like carbon nanotubes (CNTs), which enhance stability and interfacial adhesion to restrict thermal degradation and volatile diffusion, maintaining structural integrity at elevated temperatures [130]. Spark plasma sintering (SPS) minimizes grain growth, resulting in finer microstructures that improve heat dissipation and reduce thermal gradients [131], while aluminum nitride (AlN) reduces thermal expansion mismatches between matrix and reinforcements, preventing stress-induced cracking in thermal cycling applications [132]. Surface-treated CNTs boost thermal conductivity by optimizing load transfer at interfaces, making composites suitable for high-heat applications like heat sinks in electronics [133]. High-pressure homogenization further disperses CNTs and graphene, enhancing thermal management in energy systems by promoting efficient heat absorption and retention [134]. These attributes are critical under high-temperature loadings, where interfacial stability maintains structural integrity, as demonstrated in aerospace components exposed to combustion gases.

Under integrated loadings, these enhancements reveal cross-loading synergies, where mechanical gains support wear and thermal stability during fatigue, as hybrids retain 90% of properties at 400 °C [120]. For instance, TiC-reinforced systems exhibit improved tensile strength that correlates with reduced wear rates under cyclic sliding, while CNT-enhanced thermal conductivity aids in dissipating heat during dynamic impacts. Figure 15 shows the comparative trends of mechanical properties of different MMCs.

This figure illustrates comparative trends, where hybrid extrusions and Al-BNNT show the strongest dynamic impact absorption, while high-temperature retention is led by Al-Mg and Ti-TiB/TiC. Corrosion resistance is highest in hybrid extrusions, and fatigue and tensile performance vary moderately among the materials. Overall, the trends highlight how different composites excel in specific categories, emphasizing application-tailored design.

Despite these advantages, multifunctional performance enables durable, lightweight materials for aerospace applications, though limitations like reinforcement agglomeration in wear tests and thermal degradation under prolonged exposure persist. The rationale lies in meeting stringent demands for integrated durability in sectors requiring weight reduction without sacrificing resilience. Novel aspects include in situ casting experiments for Al-TiC composites, demonstrating 35% tensile strength improvements validated by fracture analysis, and proposing ML-driven FGMMCs for predictive, sustainable design that integrates bio-inspired gradients for optimized multifunctionality. This approach advances

beyond existing reviews by emphasizing holistic property interactions and experimental validation, fostering innovations for next-generation lightweight structures.

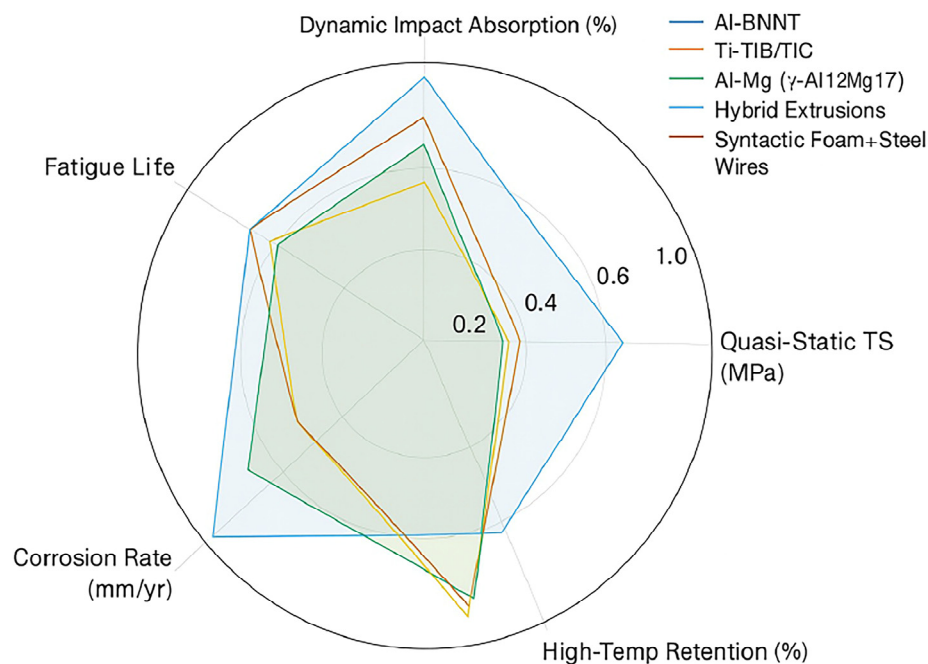


Figure 15. Properties of MMCs. Adapted from Refs. [6,58,114–117].

4.3. Emerging Trends and Future Directions

Emerging trends in the development of lightweight MMCs are reshaping the field, driven by interdisciplinary innovations that integrate bio-inspired designs, artificial intelligence (AI) and machine learning (ML), as well as sustainable materials. These advancements address long-standing challenges in MMC performance, such as balancing strength, durability, and environmental impact, while opening avenues for multifunctional applications in the aerospace, automotive, biomedical, and renewable energy sectors. This section highlights how these trends surpass previous reviews, focusing on predictive and environmentally conscious engineering. Future directions emphasize scalable production and hybrid systems, positioning MMCs as fundamental to sustainable manufacturing. The following section explores key trends and prospective paths, supported by comparative analyses and innovative proposals.

Bio-inspired designs draw from natural structures to optimize MMC microstructures, enhancing multifunctionality without compromising lightweight characteristics. For instance, mimicking bone's hierarchical architecture—where collagen fibers and hydroxyapatite provide graded interfaces—enables FGMMCs with tailored stiffness and toughness [72]. This approach reduces interfacial stress concentrations, improving fatigue life by 20–30% under cyclic loadings, as gradients dissipate energy akin to natural damping mechanisms. In syntactic foams, bio-inspired cellular arrangements, inspired by coral or trabecular bone, boost energy absorption in crash scenarios, with extrusion data showing 40% higher deformation capacity in Al-CNT hybrids. These designs facilitate self-healing interfaces via phase transformations, mitigating corrosion in physiological environments for biomedical implants. Comparative studies indicate bio-inspired Al-Mg composites outperform conventional systems in quasi-static tensile strength (25% gain) and dynamic impact resistance (35% improvement).

AI and ML are revolutionizing MMC design by enabling real-time optimization and predictive modeling, addressing variability in processing and properties. ML algorithms, trained on large datasets from microstructural simulations and experimental trials, predict

reinforcement dispersion and mechanical responses under diverse loadings [121]. For example, neural networks optimize stir casting parameters, reducing porosity by 15% and enhancing tensile strength in Ti-SiC systems. HPDC experiments integrate ML for CNT alignment prediction, achieving 35% property gains validated by electrochemical impedance spectroscopy. Future applications include closed-loop manufacturing, where sensors feed data to ML models for adaptive processing, minimizing defects in FGMSFs.

An increasing focus on sustainability is shaping the development of lightweight MMCs, with key metrics such as recyclability, CO₂ emission reduction, cost efficiency, and thermal durability guiding material selection and processing strategies. As illustrated in Figure 16, a comparative analysis of aluminum-, magnesium-, and titanium-based MMCs reveals distinct advantages and trade-offs critical for targeted applications. Magnesium-based MMCs, represented by the green area in the chart, exhibit superior recyclability and the greatest potential for CO₂ emission reduction owing to their low density and energy-efficient processing, making them attractive for environmentally conscious, cost-sensitive industries. Conversely, titanium-based MMCs (gray area) achieve the highest thermal durability, an essential attribute for high-temperature applications, such as aerospace propulsion and energy sectors, albeit at a higher cost and with moderate recyclability. Aluminum-based MMCs (blue area) strike a balance between recyclability, cost, and thermal performance, positioning themselves as versatile solutions for a broad range of engineering applications.

Sustainability metrics for Al-, Mg-, and Ti-based MMCs

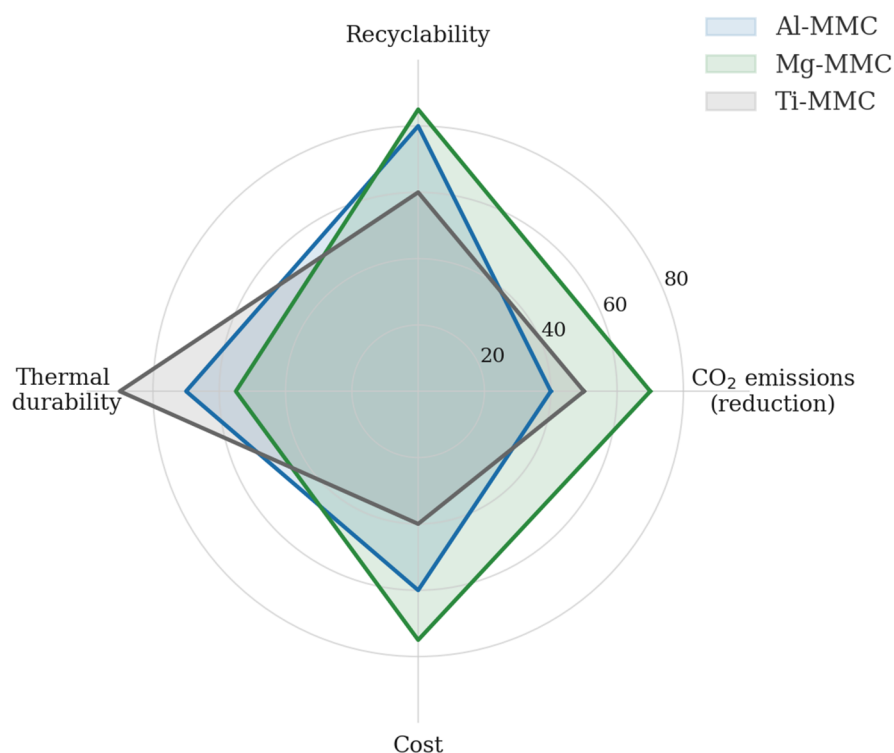


Figure 16. Sustainability metrics for aluminum- (blue), magnesium- (green), and titanium-based (gray) MMCs, comparing recyclability, CO₂ emission reduction, cost, and thermal durability. Adapted from Refs. [27,114,115].

This sustainability profile underscores the multifaceted decision-making involved in MMC design, where environmental impact and performance must align. Research supports these trends by incorporating recycled carbon nanotubes (CNTs) into extrusion

processes, demonstrating enhanced corrosion stability verified through salt spray testing, thereby reinforcing the viability of circular economy principles in MMC fabrication. The chart serves not only as a benchmark for current materials but also as a framework to guide future innovations, encouraging the integration of sustainable reinforcements and processing methods that minimize ecological footprints while maintaining or enhancing composite functionality.

Looking ahead, hybrid FGMSFs represent a promising direction, combining graded reinforcements with foam structures for superior energy absorption in automotive safety and aerospace shielding. Production via additive manufacturing could yield FGMSFs with bio-inspired layers, mimicking nacre for 50% higher impact resilience. Challenges include scaling ML for industrial adoption and mitigating agglomeration in sustainable reinforcements, but innovations like multifunctional sensors promise real-time quality control. Broader applications in renewable energy—e.g., turbine blades with CNT-enhanced thermal stability—and biomedical devices with corrosion-resistant, biocompatible MMCs, will drive demand.

5. Applications of Lightweight MMCs

Lightweight MMC has been one of the most popular candidates to the most widely studied materials, both mechanically and thermally. For aerospace, automobile, and electronics use-case, the introduction of reinforcing structures like ceramics and carbon nanotubes in a metallic matrix yields customizable performance that needs to be addressed to achieve high-performance applications. The aerospace sector is a prominent beneficiary of progress in lightweight MMC devices. The good particularity of specific strength and stiffness of MMCs render them perfect for different kind of aircraft components, like engine parts, structural panels, heat exchangers, and many more. Titanium metal matrix composites, for example, have proven better properties, including improved durability and thermal resistance and are suitable for high-temperature aerospace applications [134].

In aerospace, the adoption of MMCs leads not only to weight reductions, but also improves fuel efficiency and payload capabilities, both of which are paramount factors in aircraft design and performance. In automotive applications, MMCs enable weight reduction with no strain to the restorative construction soundness and safety. The applications span from engine parts such as pistons and cylinder heads and braking system and drive shafts to general workhorse applications. Incorporating reinforcements such as aluminum oxide, or silicon carbide to the aluminum matrices makes it possible to reduce wear and thermal properties, and to enhance engine performance [135]. Also, by designating different thermal properties to match individual users, MMCs become important for high-temperature exposure such as exhaust systems and brake components to ensure thermal stability [136]. The application for MMCs has extended to electronics where it is crucial to maintain good thermal management. Recent technology has shown that the addition of carbon nanotubes increases thermal and electrical conductivity to metal matrices leading to the possibility of applying them in electronic packaging and heat sink application [137]. The superior thermal performance of these composites is useful for efficient heat dissipation which is associated with a good thermal performance can be utilized in operation stress management, and the reliability and persistence of electronic devices has been proven. Liquid metal composites, for example, are one of them, as they have shown high thermal conductivity and can be studied for several different uses for efficient heat transfer, making them suitable candidates for an efficient heat transfer application [138].

MMCs are also popular materials for numerous industrial applications due to their high thermal resilience and material fatigue resistance and thermal stability. Composites reinforced with ceramics, for example, are used in cutting tools and machining applications,

where high hardness and thermal stability are essential to ensure tool performance during fast processing operations. In the same way, MMCs are being adopted in manufacturing processes where materials with better wear resistance and high performance are desired for efficient efficiencies and lower operating costs [139]. Lightweight MMCs are also exploring broader applications beyond the realm of traditional sectors, including renewable energy and biomedical engineering. Weighted composites to include for instance in renewable energy, for instance, lightweight composites are being explored as turbine blades and other parts or components where high strength-to-weight ratios are needed enduring extremely harsh operational conditions. In biomedical applications, MMCs are developed for surgical instruments and implants which require biocompatibility and mechanical integrity [140].

6. Conclusions

Recent years have witnessed significant advancements in the design and development of lightweight metal matrix composites (MMCs), culminating in materials that successfully integrate low density with superior mechanical, thermal, and multifunctional properties. Progress in processing technologies—including stir casting, powder metallurgy, additive manufacturing, and in situ synthesis—has enabled precise control over microstructure, reinforcement distribution, and interfacial characteristics. These innovations have collectively enhanced MMC strength, stiffness, wear resistance, corrosion behavior, and thermal stability, broadening their applicability across various engineering fields.

Complementary to advances in manufacturing, computational material design and machine learning approaches have accelerated optimization efforts by elucidating complex relationships between processing conditions, microstructural evolution, and final performance. Simultaneously, the emergence of novel reinforcements—ranging from ceramic particles and carbon-based nanostructures to multifunctional hybrid systems—has expanded the toolkit available for tailoring MMCs to stringent aerospace, automotive, defense, and energy requirements.

Despite this progress, challenges persist in achieving uniform reinforcement dispersion, scalability of low-cost production, and integration of recyclability and sustainability considerations. Future research emphasis must prioritize energy-efficient fabrication routes, predictive process modeling, and comprehensive life-cycle assessments to drive sustainable development without compromising material performance.

Sustainability metrics such as recyclability, CO₂ emission reduction, cost, and thermal durability differ markedly among aluminum-, magnesium-, and titanium-based MMCs. Magnesium-based composites excel in recyclability and environmental impact reduction due to their lightweight and energy-efficient processing, whereas titanium alloys lead in thermal durability critical for high-temperature applications, despite higher costs and moderate recyclability. Aluminum alloys offer a balanced profile, serving as versatile, cost-effective materials with reasonable thermal performance.

The findings underscore lightweight MMCs as an indispensable class of high-performance materials for next-generation structural and functional components. Realizing their full potential will depend on continued interdisciplinary collaboration—melding materials science, process engineering, and computational modeling—to successfully transition laboratory innovations into scalable, industrial solutions that harmonize high performance with ecological responsibility.

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References

1. Lajis, M.; Ahmad, A.; Yusuf, N.; Azami, A.; Wagiman, A. Mechanical properties of recycled aluminium chip reinforced with alumina (Al_2O_3) particle. *Materialwiss. Werkstofftech.* **2017**, *48*, 306–310. [\[CrossRef\]](#)
2. Velishala, M.; Pandiripalli, M.; Chilamban, V. Investigation on corrosion and wear properties of Al-7075/TiC composites fabricated by stir casting route. *Metall. Mater. Eng.* **2022**, *28*, 435–452. [\[CrossRef\]](#)
3. Jabbari, A.; Sedighi, M.; Vallant, R.; Huetter, A.; Sommitsch, C. Effect of pass number, rotational and traverse speed on particle distribution and microstructure of AZ31/SiC composite produced by friction stir processing. *Key Eng. Mater.* **2015**, 651–653, 765–770. [\[CrossRef\]](#)
4. Mohan, R.; Venkatraman, R.; Raghuraman, S.; Chidambaram, B.; Balakrishnan, S.; Vishnuram, S. An experimental study on the effect of reverse two-step sintering on aluminium-silicon carbide metal matrix composite. *Adv. Sci. Technol.* **2021**, *106*, 78–83. [\[CrossRef\]](#)
5. Liewald, M.; Riedmüller, K. Material property modification of continuous fibre-reinforced aluminium matrices produced by semi-solid forming strategies. *KMUTNB Int. J. Appl. Sci. Technol.* **2014**, *7*, 21–28. [\[CrossRef\]](#)
6. Yamaguchi, M.; Pakdel, A.; Zhi, C.; Bando, Y.; Tang, D.; Faerstein, K.; Shtansky, D.; Golberg, D. Utilization of multiwalled boron nitride nanotubes for the reinforcement of lightweight aluminum ribbons. *Nanoscale Res. Lett.* **2013**, *8*, 3. [\[CrossRef\]](#)
7. Hynes, N.; Raja, S.; Tharmaraj, R.; Pruncu, C.; Dişpınar, D. Mechanical and tribological characteristics of boron carbide reinforcement of AA6061 matrix composite. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 155. [\[CrossRef\]](#)
8. Kumar, R.; Bhowmick, H.; Gupta, D.; Bansal, S. Development and characterization of multiwalled carbon nanotube-reinforced microwave sintered hybrid aluminum metal matrix composites: An experimental investigation on mechanical and tribological performances. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2021**, *235*, 2310–2323. [\[CrossRef\]](#)
9. Bakshi, S.; Lahiri, D.; Agarwal, A. Carbon nanotube reinforced metal matrix composites—A review. *Int. Mater. Rev.* **2010**, *55*, 41–64. [\[CrossRef\]](#)
10. Malaki, M.; Tehrani, A.; Niroumand, B.; Gupta, M. Wettability in metal matrix composites. *Metals* **2021**, *11*, 1034. [\[CrossRef\]](#)
11. Natrayan, L.; Kumar, M. Mechanical, microstructure and wear behaviour of LM25/SiC/MICA metal matrix composite fabricated by squeeze casting technique. *Appl. Eng. Lett.* **2019**, *4*, 72–77. [\[CrossRef\]](#)
12. Dash, K.; Sukumaran, S.; Ray, B. The behaviour of aluminium matrix composites under thermal stresses. *Sci. Eng. Compos. Mater.* **2014**, *23*, 1–20. [\[CrossRef\]](#)
13. Pruncu, C.; Vlădescu, A.; Hynes, N.; Sankaranarayanan, R. Surface investigation of physella acuta snail shell particle reinforced aluminium matrix composites. *Coatings* **2022**, *12*, 794. [\[CrossRef\]](#)
14. Zhang, Z.; Xu, Z.; Salinas, B. In-situ disintegrating completion tools by means of controlled microgalvanic cells. In Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, LA, USA, 30 September–2 October 2013. [\[CrossRef\]](#)
15. Mishra, A.; Dixit, D.; Al-Sabur, R. Development of specially reinforced magnesium composites prepared by squeeze casting process. *Res. Eng. Struct. Mater.* **2021**, *7*, 635–646. [\[CrossRef\]](#)
16. Alam, M.; Ya, H.; Azeem, M.; Mustapha, M.; Yusuf, M.; Masood, F.; Marode, R.; Sapuan, S.; Ansari, A. Advancements in aluminum matrix composites reinforced with carbides and graphene: A comprehensive review. *Nanotechnol. Rev.* **2023**, *12*, 20230111. [\[CrossRef\]](#)
17. Senthilvelan, T.; Gopalakannan, S.; Vishnuvarthan, S.; Keerthivaran, K. Fabrication and characterization of SiC, Al_2O_3 , and B_4C reinforced Al-Zn-Mg-Cu alloy (AA 7075) metal matrix composites: A study. *Adv. Mater. Res.* **2012**, 622–623, 1295–1299. [\[CrossRef\]](#)
18. Krishna, M.; Xavior, M. An investigation on the mechanical properties of hybrid metal matrix composites. *Procedia Eng.* **2014**, *97*, 918–924. [\[CrossRef\]](#)
19. Thayumanavan, M.; Kumar, K. Fabrication and mechanical behaviour investigation on aluminium 7075 boron carbide and Inconel alloy 625 metal matrix composite using ultra sonic stir casting method. *Ann. Chim.-Sci. Mat.* **2022**, *46*, 333–338. [\[CrossRef\]](#)
20. Karthikeyan, A.; Nallusamy, S. Experimental analysis on sliding wear behaviour of aluminium-6063 with SiC particulate composites. *Int. J. Eng. Res. Afr.* **2017**, *31*, 36–43. [\[CrossRef\]](#)
21. Monikandan, V.; Prasanth, P.; Dhas, E. Investigation on casting anomalies of liquid metallurgy—Processed aa 6061- B_4C composites. *Int. J. Sci. Res. Eng. Manag.* **2024**, *08*, 1–14. [\[CrossRef\]](#)
22. Bodunrin, M.; Alaneme, K.; Chown, L. Aluminium matrix hybrid composites: A review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *J. Mater. Res. Technol.* **2015**, *4*, 434–445. [\[CrossRef\]](#)

23. Dolata-Grosz, A.; Dyzia, M.; Walke, W. Influence of particles type and shape on the corrosion resistance of aluminium hybrid composites. *Solid State Phenom.* **2012**, *191*, 81–87. [\[CrossRef\]](#)
24. Uvaraja, V.; Natarajan, N. Optimization of friction and wear behaviour in hybrid metal matrix composites using taguchi technique. *J. Miner. Mater. Charact. Eng.* **2012**, *11*, 757–768. [\[CrossRef\]](#)
25. Popov, V.; Pismenny, A.; Larianovsky, N.; Ларионова, А.; Safranchik, D. Corrosion resistance of Al–CNT metal matrix composites. *Materials* **2021**, *14*, 3530. [\[CrossRef\]](#)
26. Simões, S.; Viana, F.; Reis, M.A.L.; Vieira, M.F. Aluminum and Nickel Matrix Composites Reinforced by CNTs: Dispersion/Mixture by Ultrasonication. *Metals* **2017**, *7*, 279. [\[CrossRef\]](#)
27. Carneiro, Í.; Simões, S. Investigation of Mechanical Properties of Al/CNT Nanocomposites Produced by Powder Metallurgy. *Appl. Sci.* **2023**, *13*, 54. [\[CrossRef\]](#)
28. Pomorska, M.; Kaczmar, J.; Morgiel, J.; Naplocha, K. TEM investigation of interfaces formed between Saffil™ fibers and AA6061 and En Ac 44200 aluminium alloys. *Solid State Phenom.* **2012**, *186*, 327–330. [\[CrossRef\]](#)
29. Hossain, M.; Ali, M.; Amin, M.; Kibria, M.; Ferdous, M. Fabrication and performance test of aluminium alloy-rice husk ash hybrid metal matrix composite as industrial and construction material. *Int. J. Eng. Mater. Manuf.* **2017**, *2*, 94–102. [\[CrossRef\]](#)
30. Kartal, Y.; Er, A. Investigation the machinability of aluminium (Al1070) matrix silicium carbide (SiC) and boron carbide (B4C) hybrid reinforced composite materials. *Int. J. Eng. Res.* **2024**, *16*, 47–55. [\[CrossRef\]](#)
31. Blanco, D.; Rubio, E.; Lorente-Pedreille, R.; Nuño, M. Sustainable processes in aluminium, magnesium, and titanium alloys applied to the transport sector: A review. *Metals* **2021**, *12*, 9. [\[CrossRef\]](#)
32. Szczepanik, S.; Nikiel, P.; Bednarczyk, P. Influence of cold working on mechanical properties of Al–SiC composites. *Mater. Sci. Forum* **2017**, *892*, 53–58. [\[CrossRef\]](#)
33. Jayasathyakawin, S.; Ravichandran, M.; Mohanavel, V.; Sathish, T.; Kumar, S.; Rajkumar, S.; Subbiah, R. A review on exploration of magnesium matrix composites. *Mater. Sci. Forum* **2022**, *1068*, 63–70. [\[CrossRef\]](#)
34. Abbas, A.; Rajagopal, V.; Huang, S. Magnesium metal matrix composites and their applications. In *Magnesium Alloys Structure and Properties Edited by Tomasz Tański and Paweł Jarka*; IntechOpen: London, UK, 2022. [\[CrossRef\]](#)
35. Balakrishnan, M.; Dinaharan, I.; Palanivel, R.; Sivaprakasam, R. Synthesize of AZ31/TiC magnesium matrix composites using friction stir processing. *J. Magnes. Alloys* **2015**, *3*, 76–78. [\[CrossRef\]](#)
36. Gotagunaki, S.; Mudakappanavar, V.; Suresh, R. Investigation on microstructure and tensile fractography of re oxides (CeO₂/Y₂O₃) reinforced AZ91D magnesium matrix composites. *Frat. Integrità Strut.* **2022**, *17*, 100–109. [\[CrossRef\]](#)
37. Matta, A.; Koka, N.; Devarakonda, S. Recent studies on particulate reinforced AZ91 magnesium composites fabricated by stir casting—A review. *J. Mech. Energy Eng.* **2020**, *4*, 115–126. [\[CrossRef\]](#)
38. Raju, G.; Meti, V.; Banapurmath, N.; Khan, T.; Siddhalingeswar, I.; Vaikunte, V.; Vadlamudi, C.; Krishnappa, S.; Patil, A. Effect of multi-walled carbon nanotubes and carbon fiber reinforcements on the mechanical and tribological behavior of hybrid Mg–AZ91D nanocomposites. *Materials* **2022**, *15*, 6181. [\[CrossRef\]](#)
39. Liu, J.; Zhou, Y.; Zi, X. Study on mechanical property of SiC particulate reinforced magnesium matrix composites prepared by powder metallurgy. *Appl. Mech. Mater.* **2012**, 246–247, 1106–1110. [\[CrossRef\]](#)
40. Yan, H.; Huang, X.; Hu, Q. Damping capacity of SiCp/AZ61 composites. *Adv. Mater. Res.* **2010**, 123–125, 35–38. [\[CrossRef\]](#)
41. Deng, K.; Wu, K.; Wu, Y.; Nie, K.; Zheng, M. Effect of submicron size SiC particulates on microstructure and mechanical properties of AZ91 magnesium matrix composites. *J. Alloys Compd.* **2010**, *504*, 542–547. [\[CrossRef\]](#)
42. Castro, M.; Lopes, D.; Soares, R.; Santos, D.; Nunes, E.; Lins, V.; Pereira, H.; Isaac, A.; Langdon, T.G.; Figueiredo, R. Magnesium-based bioactive composites processed at room temperature. *Materials* **2019**, *12*, 2609. [\[CrossRef\]](#)
43. Zhou, J.; Qi, L.; Ouyang, H.; Li, H. Mechanical properties of Csf/AZ91D composites fabricated by extrusion forming process directly following the vacuum infiltration. *Adv. Mater. Res.* **2010**, 89–91, 692–696. [\[CrossRef\]](#)
44. Liu, S. Mechanical and wear behavior of self-lubricating hybrid metal matrix composite (MMC). *Highl. Sci. Eng. Technol.* **2024**, *116*, 226–236. [\[CrossRef\]](#)
45. Mohr, M.; Wunderlich, R.; Novaković, R.; Ricci, E.; Fecht, H. Precise measurements of thermophysical properties of liquid Ti–6Al–4V (Ti64) alloy on board the international space station. *Adv. Eng. Mater.* **2020**, *22*, 2000169. [\[CrossRef\]](#)
46. Hughes, J.; Sharman, A.; Ridgway, K. The effect of tool edge preparation on tool life and workpiece surface integrity. *Proc. Inst. Mech. Eng. Pt. B J. Eng. Manufact.* **2004**, *218*, 1113–1123. [\[CrossRef\]](#)
47. Huang, Z.; Lu, D.; Zhang, Y.; Jiang, Y.; Lu, Y.; Guo, Y. Mechanical performance and failure modes of self-piercing riveted joints between AA6061 and solution-treated TC4 alloy. *Mater. Res. Express* **2023**, *10*, 056510. [\[CrossRef\]](#)
48. Safavi, M.; Balazinski, M.; Mehmanparast, H.; Niknam, S. Experimental characterization of tool wear morphology and cutting force profile in dry and wet turning of titanium metal matrix composites (Ti–MMCs). *Metals* **2020**, *10*, 1459. [\[CrossRef\]](#)
49. Gardiola, B.; Andrieux, J.; Viala, J.; Dezellus, O. Synthesis of Ti matrix composites reinforced with tic particles: Thermodynamic equilibrium and change in microstructure. *J. Mater. Sci.* **2016**, *52*, 4129–4141. [\[CrossRef\]](#)

50. Markovsky, P.; Janiszewski, J.; Stasyuk, O.; Bondarchuk, V.; Savvakina, D.; Cieplak, K.; Goran, D.; Soni, P.; Prikhodko, S. Mechanical behavior of titanium based metal matrix composites reinforced with TiC or TiB particles under quasi-static and high strain-rate compression. *Materials* **2021**, *14*, 6837. [\[CrossRef\]](#)
51. Zhang, S.; Li, Q.; Ho, M.; Pook, S.; Chandra, M.; Yong, M. Microstructural investigation of particulate reinforced Ti-Sn metal matrix composites. *Solid State Phenom.* **2006**, *111*, 35–38. [\[CrossRef\]](#)
52. Devesa, F.; Rial, S.; Amigó, V. Processing and characterization of β -Ti alloys by means of powder metallurgy processing and blender elemental. *Mater. Sci. Forum* **2012**, 727–728, 61–66. [\[CrossRef\]](#)
53. Das, D.; Mishra, P.; Singh, S.; Pattanaik, S. Fabrication and heat treatment of ceramic-reinforced aluminium matrix composites—A review. *Int. J. Mech. Mater. Eng.* **2014**, *9*, 6. [\[CrossRef\]](#)
54. Moser, N.; Staufer, E.; Klein, T.; Horky, J.; Schmitz-Niederau, M.; Neubauer, E.; Trunova, L.; Edtmaier, C. Preparation and characterization of Ti-6-4 and Ti-8-1-1 metal matrix composites with high specific stiffness using powder hot extrusion and arc remelting. *Adv. Eng. Mater.* **2024**, *26*, 2400514. [\[CrossRef\]](#)
55. Rabiei, A.; O'Neill, A. A study on processing of a composite metal foam via casting. *Mater. Sci. Eng. A* **2005**, *404*, 159–164. [\[CrossRef\]](#)
56. Sharma, S.; Rajpoot, Y. Development of aluminum metal foam using blowing agent. *IOP Conf. Ser. Mat. Scien. Engin.* **2018**, *377*, 012150. [\[CrossRef\]](#)
57. Gandhapu, S.; Mahajan, A.; Sasikumar, S. Cell structure improvement in melt processed pure aluminium foams by pre-treatment of foaming mixture. *IOP Conf. Ser. Mat. Scien. Engin* **2022**, *1248*, 012038. [\[CrossRef\]](#)
58. Husain, F.; Siddiquee, A.; Khan, Z. Fabrication routes of aluminium metal foams: A review. In Proceedings of the 2022 2nd Indian International Conference on Industrial Engineering and Operations Management, Warangal, India, 16–18 August 2022. [\[CrossRef\]](#)
59. Rabiei, A.; Karimpour, K.; Janssens, M.; Basu, D. Simulated pool fire testing and modeling of a composite metal foam. *Fire Mater.* **2020**, *45*, 379–386. [\[CrossRef\]](#)
60. Rabiei, A.; Cance, J.; Chacko, Z. A study on welding of porous metals and metallic foams. *Adv. Eng. Mater.* **2023**, *26*, 2301430. [\[CrossRef\]](#)
61. Szovák, B.; Kemény, A.; Orbulov, I. Unidirectional steel wire reinforced metal matrix syntactic foams. *IOP Conf. Ser. Mater. Sci. Eng.* **2024**, *1319*, 012007. [\[CrossRef\]](#)
62. Zheng, J.; Wang, T.; Chen, T.; Yu, Y. Effect of pore distribution on melting behavior of paraffin in fractal metal foam. *Commun. Theor. Phys.* **2018**, *70*, 501. [\[CrossRef\]](#)
63. Feng, B.; Li, D.; Rong, Y.; Gao, J.; Zhou, J.; Luo, G. Experimental transient performance of heat sink with phase change material and movable metal foams insert. *J. Phys. Conf. Ser.* **2023**, *2598*, 012011. [\[CrossRef\]](#)
64. Liu, Y.; Zhou, W.; Chu, X.; Liu, S.; Hui, K. Feasibility investigation of direct laser cutting process of metal foam with high pore density. *Int. J. Adv. Manuf. Technol.* **2018**, *96*, 2803–2814. [\[CrossRef\]](#)
65. Cui, C.; Sun, J. Optimizing the design of bio-inspired functionally graded material (FGM) layer in all-ceramic dental restorations. *Dent. Mater. J.* **2014**, *33*, 173–178. [\[CrossRef\]](#)
66. Singh, R.; Singh, R. Property investigation of functionally graded materials leaf spring plate fabricated through stir casting process by using new gradient evaluation method. *Materialwiss. Werkstofftech.* **2024**, *55*, 1297–1309. [\[CrossRef\]](#)
67. Chmielewski, M.; Pietrzak, K. Metal-ceramic functionally graded materials—Manufacturing, characterization, application. *Bull. Pol. Acad. Sci. Tech. Sci.* **2016**, *64*, 151–160. [\[CrossRef\]](#)
68. Shareef, M.; Al-Khazraji, A.; Amin, S. Bending properties of a functionally graded polymeric composite reinforced with a hybrid nanomaterial. *Iraqi J. Mech. Mater. Eng.* **2021**, *21*, 302–319. [\[CrossRef\]](#)
69. Jabbar, N.; Hussain, I.; Abdullah, O.; Mohammed, M. An experimental investigation and numerical analysis of the thermal behavior of a clutch system using the frictional facing of functionally graded materials. *Designs* **2023**, *7*, 125. [\[CrossRef\]](#)
70. Arsha, A.; Jayakumar, E.; Rajan, T.; Pai, B. Processing and characterization of functionally graded In Situ aluminum composite. *Mater. Sci. Forum* **2015**, 830–831, 485–488. [\[CrossRef\]](#)
71. Genc, S.; Taskin, N. New processing route for the production of functionally graded 7075 Al/SiCp composites via a combination of semisolid stirring and sequential squeeze casting. *Crystals* **2024**, *14*, 297. [\[CrossRef\]](#)
72. Wu, D.; Liang, X.; Li, Q.; Jiang, L. Laser rapid manufacturing of stainless steel 316L/Inconel718 functionally graded materials: Microstructure evolution and mechanical properties. *Int. J. Opt.* **2010**, *2010*, 1–5. [\[CrossRef\]](#)
73. Mohandas, A.; Radhika, N. Studies on mechanical behaviour of aluminium/nickel coated silicon carbide reinforced functionally graded composite. *Tribol. Ind.* **2017**, *39*, 145–151. [\[CrossRef\]](#)
74. Surya, M.; Prasanthi, G. Tribological behaviour of aluminum silicon carbide functionally graded material. *Tribol. Ind.* **2018**, *40*, 247–253. [\[CrossRef\]](#)
75. Niu, X.; Rahbar, N.; Farias, S.; Soboyejo, W. Bio-inspired design of dental multilayers: Experiments and model. *J. Mech. Behav. Biomed. Mater.* **2009**, *2*, 596–602. [\[CrossRef\]](#)

76. Mohn, W.; Vukobratovich, D. Engineered metal matrix composites for precision optical systems., Proceedings Volume 0817, Optomechanical Systems Engineering. In Proceedings of the 31st Annual Technical Symposium on Optical and Optoelectronic Applied Sciences and Engineering, San Diego, CA, USA, 17–21 August 1987; Volume 817, p. 181. [\[CrossRef\]](#)
77. Bhoi, N.; Singh, H.; Pratap, S. Developments in the aluminum metal matrix composites reinforced by micro/nano particles—A review. *J. Compos. Mater.* **2019**, *54*, 813–833. [\[CrossRef\]](#)
78. Sambathkumar, M.; Gukendran, R.; Mohanraj, T.; Karupannasamy, D.; Natarajan, N.; Christopher, D. A systematic review on the mechanical, tribological, and corrosion properties of Al 7075 metal matrix composites fabricated through stir casting process. *Adv. Mater. Sci. Eng.* **2023**, *2023*, 1–17. [\[CrossRef\]](#)
79. Liu, Y.; Kumar, S. Polymer/carbon nanotube nano composite fibers—a review. *Acs Appl. Mater. Interfaces* **2014**, *6*, 6069–6087. [\[CrossRef\]](#)
80. Merino, C.; Meza, J.; Ledezma-Sillas, J.; Ramírez, J. Characterization of metal matrix composites reinforced with carbon nanotubes by high resolution transmission electron microscopy. *Microsc. Microanal.* **2017**, *23*, 1926–1927. [\[CrossRef\]](#)
81. Anthymidis, K.; David, C.; Trakali, A.; Agrianidis, P. Characterization of al metal matrix composites produced by the stir-casting method. *Key Eng. Mater.* **2013**, *577–578*, 85–88. [\[CrossRef\]](#)
82. Sougavabar, M.; Niknam, S.; Davoodi, B.; Songmené, V. Milling Al520-MMC reinforced with SiC particles and additive elements Bi and Sn. *Materials* **2022**, *15*, 1533. [\[CrossRef\]](#) [\[PubMed\]](#)
83. Sarmah, P.; Gupta, K. Recent Advancements in Fabrication of Metal Matrix Composites: A Systematic Review. *Materials* **2024**, *17*, 4635. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Aynalem, G. Processing methods and mechanical properties of aluminium matrix composites. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 3765791. [\[CrossRef\]](#)
85. Ali, S.; Bhaskar, K.; Raju, K. A review on distribution of reinforcement and tensile strength of aluminum lithium alloy based nano metal matrix composites fabricated by stir casting. *J. Phys. Conf. Ser.* **2024**, *2765*, 012023. [\[CrossRef\]](#)
86. Gaohong, C.; Yu, M.; Dong, H.; Liu, J. Experimental investigation into the preparation process of graphene-reinforced aluminum matrix composites by friction stirring processing. *Materials* **2024**, *17*, 3918. [\[CrossRef\]](#)
87. Andilab, B.; Emadi, P.; Ravindran, C. Casting and characterization of A319 aluminum alloy reinforced with graphene using hybrid semi-solid stirring and ultrasonic processing. *Materials* **2022**, *15*, 7232. [\[CrossRef\]](#)
88. Ali, S.; Murtaza, Q.; Gupta, P. Evaluation of phase, microstructural and mechanical characteristics in stir casted AA6351-Gr-TiC hybrid metal matrix composites. *Proc. Inst. Mech. Eng. Pt. C J. Mechan. Eng. Sci.* **2023**, *238*, 5097–5112. [\[CrossRef\]](#)
89. Abood, A.; Jayanthi, M.; Anjaneyulu, M.; Thethi, H.; Singh, S.; Chahuan, N. Advancing aluminum-based composite manufacturing: Leveraging WC reinforcement through stir casting technique. *E3s Web Conf.* **2024**, *507*, 01040. [\[CrossRef\]](#)
90. Maji, P.; Ghosh, S.; Nath, R.; Karmakar, R. Microstructural, mechanical and wear characteristics of aluminum matrix composites fabricated by friction stir processing. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 191. [\[CrossRef\]](#)
91. Mohammad, Q.; Borah, A.R.; Ram, K.R.P.; Nagpal, A.; Chauhan, S.; Meheta, A. Advancements in aluminum-based composite manufacturing: Leveraging ZrO₂ reinforcement through friction stir process. *E3s Web Conf.* **2024**, *507*, 01020. [\[CrossRef\]](#)
92. Vij, V.; Agarwal, R.; Garg, M.; Khanna, R.; Gupta, V. Fabrication and mechanical characterization of hybrid composite reinforced with nanoparticles of alumina and zirconia. *Polym. Compos.* **2022**, *43*, 7315–7325. [\[CrossRef\]](#)
93. Ding, W.; Cheng, Y.; Chen, T.; Zhao, X.; Liu, X. Research status and application prospect of aluminum matrix composites. *J. Mater. Sci. Res.* **2020**, *2*. [\[CrossRef\]](#)
94. Dudina, D.; Georgarakis, K.; Olevsky, E. Progress in aluminium and magnesium matrix composites obtained by spark plasma, microwave and induction sintering. *Int. Mater. Rev.* **2022**, *68*, 225–246. [\[CrossRef\]](#)
95. Liang, J.; Wu, C.; Zhao, Z.; Tang, W. Forming process and simulation analysis of helical carbon fiber reinforced aluminum matrix composite. *Metals* **2021**, *11*, 2024. [\[CrossRef\]](#)
96. Ali, A.; Hafez, W. Overcoming challenges in the powder metallurgy process of metal matrix composites. *SVU-Int. J. Appl. Eng. Sci.* **2023**, *5*, 13–18. [\[CrossRef\]](#)
97. Fatchurrohman, N.; Mamat, A.; Yetrina, M.; Muhida, R. Investigation of metal matrix composites aluminium reinforced graphite particles produced using powder metallurgy. *J. Teknol.* **2022**, *12*, 76–81. [\[CrossRef\]](#)
98. Azadi, M.; Zomorodipour, M.; Fereidoon, A. Sensitivity analysis of mechanical properties and ductile/brittle behaviors in aluminum-silicon alloy to loading rate and nano-particles, considering interaction effects. *Eng. Rep.* **2020**, *3*, e12341. [\[CrossRef\]](#)
99. Arma, M.L.; Syahid, M. The Effect of Hot Pressing on the Mechanical Properties of Metal Composites (Al/SiC) Result from Metallurgical Processes with Heating Temperature Variations in Bushing Making. *EPI Int. J. Eng.* **2023**, *6*, 24–27. [\[CrossRef\]](#)
100. Sames, W.; List, F.; Pannala, S.; Dehoff, R.; Babu, S. The metallurgy and processing science of metal additive manufacturing. *Int. Mater. Rev.* **2016**, *61*, 315–360. [\[CrossRef\]](#)
101. Gu, D.; Meiners, W.; Wissenbach, K.; Poprawe, R. Laser additive manufacturing of metallic components: Materials, processes and mechanisms. *Int. Mater. Rev.* **2012**, *57*, 133–164. [\[CrossRef\]](#)

102. Bernard, G.; Pejchal, V.; Sereda, O.; Logé, R.E. Tensile Properties of Ex-Situ Ti-TiC Metal Matrix Composites Manufactured by Laser Powder Bed Fusion. *Materials* **2024**, *17*, 5613. [\[CrossRef\]](#)
103. Dhandapani, S.; Rajmohan, T.; Palanikumar, K.; Mugunthan, C. Preparation and characterization of hybrid aluminum matrix composites reinforced with MWCNT using powder metallurgy process. *Appl. Mech. Mater.* **2015**, *813–814*, 620–624. [\[CrossRef\]](#)
104. Mahboob, H.; Sajjadi, S.; Zebarjad, S. Influence of nanosized Al₂O₃ weight percentage on microstructure and mechanical properties of Al-matrix nanocomposite. *Powder Metall.* **2011**, *54*, 148–152. [\[CrossRef\]](#)
105. Özel, S.; Aslan, K. Investigation of the effect of Cr₂O₃ particles on Al-Si matrix composites produced by powder metallurgy. *Bitlisfen* **2023**, *12*, 387–395. [\[CrossRef\]](#)
106. Ravichandran, M.; Manikandan, A.; Omkumar, M. Investigations on properties of Al-B₄C composites synthesized through powder metallurgy route. *Appl. Mech. Mater.* **2016**, *852*, 93–97. [\[CrossRef\]](#)
107. Plötz, S.; Lohmüller, A.; Singer, R. Influence of Ti and Zn on particle incorporation of Al particles in aluminum using the stir casting process. *Key Eng. Mater.* **2017**, *742*, 173–180. [\[CrossRef\]](#)
108. Juang, S.H.; Li, C.-F. Influence of Different Addition Ratios of Fly Ash on Mechanical Properties of ADC10 Aluminum Matrix Composites. *Metals* **2022**, *12*, 653. [\[CrossRef\]](#)
109. Kumar, B.; Shobha, K.; Singh, M.; Rinawa, M.; Madhavarao, S.; Wadhawa, G.; Alrebdi, T.A.; Christopher, D. Optimization and wear properties for the composites of metal matrix AA8011/boron nitride using taguchi method. *J. Nanomater.* **2022**, *2022*, 6957545. [\[CrossRef\]](#)
110. Kumar, S.; Chaganty, S.; Rajesh, V.; Reddy, K.; Babu, N.; Shnain, A. Review on development, nanoparticle reinforcement and sustainable materials for enhancement of mechanical properties in aluminium hybrid metal matrix composites. *E3s Web Conf.* **2024**, *552*, 01068. [\[CrossRef\]](#)
111. Rajesh, T.; Narayana, B.; Kumar, M.; Natarajan, T. Development and characterization of C355.0 alloy composite for automotive applications—A review. *J. Mines Met. Fuels.* **2023**, *71*, 260–273. [\[CrossRef\]](#)
112. Rathod, N.; Menghani, J. A consequence of reinforcements in aluminum-based metal matrix composites: A literature review. *Metall. Mater. Eng.* **2019**, *25*, 195–208. [\[CrossRef\]](#)
113. Rey, P.; González-Doncel, G. Advances in lightweight metal matrix composites. *Metals* **2025**, *15*, 160. [\[CrossRef\]](#)
114. Arévalo, C.; Montealegre-Meléndez, I.; Ariza, E.; Kitzmantel, M.; Rubio-Escudero, C.; Neubauer, E. Influence of sintering temperature on the microstructure and mechanical properties of in situ reinforced titanium composites by inductive hot pressing. *Materials* **2016**, *9*, 919. [\[CrossRef\]](#)
115. Shahid, R.; Scudino, S. Microstructure and mechanical behavior of Al-Mg composites synthesized by reactive sintering. *Metals* **2018**, *8*, 762. [\[CrossRef\]](#)
116. Reeb, A.; Schulze, V.; Weidenmann, K. Interface characterization of hybrid composite extrusions. *Mater. Sci. Forum* **2015**, *825–826*, 134–141. [\[CrossRef\]](#)
117. Patel, M.; Sahu, S.; Singh, M. Fabrication and investigation of mechanical properties of sic particulate reinforced AA5052 metal matrix composite. *J. Mod. Mater.* **2020**, *7*, 26–36. [\[CrossRef\]](#)
118. Farid, W.; Li, H.; Wang, Z.; Cui, H.; Kong, C.; Yu, H. Integrating experimental and computational analyses for mechanical characterization of titanium carbide/aluminum metal matrix composites. *Materials* **2024**, *17*, 2093. [\[CrossRef\]](#) [\[PubMed\]](#)
119. Cao, F.; Zhang, X.; Dong, G.; Jiang, Y.; Gao, F.; Cai, P.; Cai, P.; Wang, T.; Liang, S. Microstructures and properties of in situ (TiB₂p+TiB_w)/Cu composites with different Ce content. *Adv. Eng. Mater.* **2022**, *24*, 2200251. [\[CrossRef\]](#)
120. Zhu, D.; Dong, D.; Liu, L.; Wang, X.; Qi, J. Control of the lamellar structure and analysis of tensile properties of TiC/Ti-6Al-3Sn-9Zr-1.5Mo composite produced by in situ casting technique. *Metals* **2021**, *11*, 160. [\[CrossRef\]](#)
121. Kordijazi, A.; Zhao, T.; Zhang, J.; Alrfou, K.; Rohatgi, P. A review of application of machine learning in design, synthesis, and characterization of metal matrix composites: Current status and emerging applications. *JOM* **2021**, *73*, 2060–2074. [\[CrossRef\]](#)
122. Gupta, P.; Gupta, M. Mechanical and microstructural analysis of Al-Al₂O₃/B₄C hybrid composites. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2020**, *234*, 1503–1514. [\[CrossRef\]](#)
123. Murmu, S.; Chattopadhyaya, S.; Čep, R.; Kumar, A.; Kumar, A.; Mahato, S.; Kumar, A.; Logesh, K. Exploring tribological properties in the design and manufacturing of metal matrix composites: An investigation into the Al6061-SiC-fly ash alloy fabricated via stir casting process. *Front. Mater.* **2024**, *11*, 1415907. [\[CrossRef\]](#)
124. Alizadeh, A.; Taheri-Nassaj, E.; Baharvandi, H. Preparation and investigation of Al-4 wt % B₄C nanocomposite powders using mechanical milling. *Bull. Mater. Sci.* **2011**, *34*, 1039–1048. [\[CrossRef\]](#)
125. Balasubramani, V.; Pandiarajan, R.; Stalin, B.; Kavimani, V. Mechanical and metallurgical characterization of B₄C and SiC reinforced stir casted AA6061 hybrid mmc. *Phys. Scr.* **2023**, *98*, 105922. [\[CrossRef\]](#)
126. Xu, Z.; Shi, X.; Zhai, W.; Yao, J.; Song, S.; Zhang, Q. Preparation and tribological properties of TiAl matrix composites reinforced by multilayer graphene. *Carbon* **2014**, *67*, 168–177. [\[CrossRef\]](#)

127. Sureshkumar, P.; Sasikumar, C.; Rajan, S.; Jagadeesha, T.; Natrayan, L.; Ravichandran, M.; Veeman, D.; Borek, W. Evaluation of mechanical and wear properties of AA6063/(Si₃N₄)_{6%–12%}/(CuN₂O₆)_{2%–4%} composite via pm route and optimization through robust design technique. *Mater. Res. Express* **2022**, *9*, 076502. [\[CrossRef\]](#)
128. Shuvho, M.; Chowdhury, M.; Hossain, N.; Roy, B.; Kowser, M.; Islam, A. Tribological study of al-6063-based metal matrix embedded with SiC–Al₂O₃–TiO₂ particles. *SN Appl. Sci.* **2020**, *2*, 287. [\[CrossRef\]](#)
129. Venkatesh, V.; Deoghare, A. Effect of controllable parameters on the tribological behavior of ceramic particulate reinforced aluminium metal matrix composites: A review. *J. Phys. Conf. Ser.* **2020**, *1451*, 012025. [\[CrossRef\]](#)
130. Yan, D.; Dai, K.; Xiang, Z.; Li, Z.; Ji, X.; Zhang, W. Electrical conductivity and major mechanical and thermal properties of carbon nanotube-filled polyurethane foams. *J. Appl. Polym. Sci.* **2011**, *120*, 3014–3019. [\[CrossRef\]](#)
131. Yu, S.; Shin, K. Fabrication of aluminum/aluminum nitride composites by reactive mechanical alloying. *Mater. Sci. Forum* **2007**, *534–536*, 181–184. [\[CrossRef\]](#)
132. Yadav, V.; Harimkar, S. Microstructure and properties of spark plasma sintered carbon nanotube reinforced aluminum matrix composites. *Adv. Eng. Mater.* **2011**, *13*, 1128–1134. [\[CrossRef\]](#)
133. Li, H.; Shuai, L.; Tu, K.; Zeng, M.; Yan, H. Microstructure and mechanical properties of 7075 composites reinforced with tio2-coated carbon nanotubes. *Proc. Inst. Mech. Eng. Part E J. Process. Mech. Eng.* **2023**, *239*, 129–139. [\[CrossRef\]](#)
134. Shin, S.; Lee, D.; Lee, Y.; Ko, S.; Park, H.; Lee, S.; Kim, Y.; Lee, S.-K.; Jo, I. High temperature mechanical properties and wear performance of B₄C/Al7075 metal matrix composites. *Metals* **2019**, *9*, 1108. [\[CrossRef\]](#)
135. Pardo, Á.; Merino, M.; López, M.; Viejo, F.; Carboneras, M.; Merino, S. Influence of reinforcement grade and matrix composition on corrosion resistance of cast aluminium matrix composites (A3xx.x/SiC_p) in a humid environment. *Mater. Corros.* **2003**, *54*, 311–317. [\[CrossRef\]](#)
136. Venkatesh, R.; Sakthivel, P.; Vivekanandan, M.; Chidambaram, K.; Krishna, J.; Dhanabalan, S.; Thirugnanasambandham, T.; Majora, M. Synthesis and thermal adsorption characteristics of silver-based hybrid nanocomposites for automotive friction material application. *Adsorp. Sci. Technol.* **2023**, *2023*, 1003492. [\[CrossRef\]](#)
137. Li, B.; Zhou, L.; Wang, B.; Yin, M.; Qian, Y.; Shi, X.; Guo, Z.; Han, Z.; Sun, L. Nanoscale dispersion of carbon nanotubes in a metal matrix to boost thermal and electrical conductivity via facile ball milling techniques. *Nanomaterials* **2023**, *13*, 2815. [\[CrossRef\]](#) [\[PubMed\]](#)
138. Wang, H.; Xing, W.; Shen, C.; Song, C.; Dickey, M.; Deng, T. Liquid metal composites with enhanced thermal conductivity and stability using molecular thermal linker. *Adv. Mater.* **2021**, *33*, 2103104. [\[CrossRef\]](#) [\[PubMed\]](#)
139. Chawla, N.; Chawla, K. Metal-matrix composites in ground transportation. *JOM* **2006**, *58*, 67–70. [\[CrossRef\]](#)
140. Mahesha, C.; Suprabha, R.; Harne, M.; Galme, S.; Thorat, S.; Nagabhooshanam, N.; Seikh, A.H.; Siddique, M.H.; Markos, M. Nanotitanium oxide particles and jute-hemp fiber hybrid composites: Evaluate the mechanical, water absorptions, and morphological behaviors. *J. Nanomater.* **2022**, *2022*, 3057293. [\[CrossRef\]](#)

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