



Review on Hybrid Aluminium MMCs: Reinforcement Strategies and Processing Techniques for Advanced Applications

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Abstract: Aluminium Metal Matrix Composites (AMMCs), particularly Hybrid AMMCs (HAMMCs), have emerged as promising materials for advanced engineering applications due to their superior strength-to-weight ratio, wear resistance, and customizable properties. This review examines the fabrication methods and reinforcement strategies employed to enhance the performance of AMMCs. Stir casting remains the most widely adopted technique, valued for its simplicity, cost-efficiency, and scalability. The integration of diverse reinforcements including ceramics (SiC, B₄C, Al₂O₃), nanomaterials (MWCNTs, Gr), and agro-waste byproducts (e.g., Rice Husk Ash) is shown to improve mechanical, tribological, and corrosion properties. Boron carbide (B₄C), in particular, enhances strength and hardness, with particle size and distribution playing a crucial role in final composite behavior. Fine particles improve properties but risk agglomeration, while coarser particles ensure better dispersion. Advanced processing techniques, such as plasma-activate sintering, microwave treatment, and wettability-enhanced stir casting, contribute to improved matrix reinforcement bonding and uniform dispersion. The evolution toward hybrid reinforcement systems demonstrates a strategic shift toward sustainable, high-performance, and application-specific materials, making HAMMCs ideal candidates for aerospace, automotive, and industrial sectors.

1. Introduction

In today's world, industries such as automotive, aerospace, marine, and sports equipment face numerous challenges related to performance demands, the need for lightweight components, and the pursuit of improved efficiency and functionality. To address these challenges, there is a growing need for the development of advanced materials and innovative manufacturing techniques. A bibliometric analysis within the paper shows an exponential rise in global research on biocomposites, with India, China, and Malaysia leading in publications. The mapping of research collaborations (via VOSviewer) highlights expanding international interest and the growing industrial relevance of sustainable composites (Latifi *et al.*, 2024; Byiringiro *et al.*, 2025; El Magri *et al.*, 2025; Igwe *et al.*, 2025; Kumar *et al.*, 2025). In this context, Metal Matrix Composites (MMCs) have emerged as promising materials that offer tailored properties to meet specific performance requirements. The primary objective in designing metal matrix composites (MMCs) is to integrate the beneficial characteristics of both metals

and ceramics. By incorporating high-strength, high-modulus refractory particles into a ductile metal matrix, the resulting composite exhibits mechanical properties that lie between those of the base metal alloy and the ceramic reinforcement.

Aluminium is the most abundant metal in the Earth's crust and the third most abundant element overall, after oxygen and silicon. It constitutes approximately 8% by weight of the Earth's solid surface (Chawla, 1998). Due to its easy availability, high strength-to-weight ratio, excellent machinability, durability, ductility, and malleability, aluminium has become the most widely used non-ferrous metal.

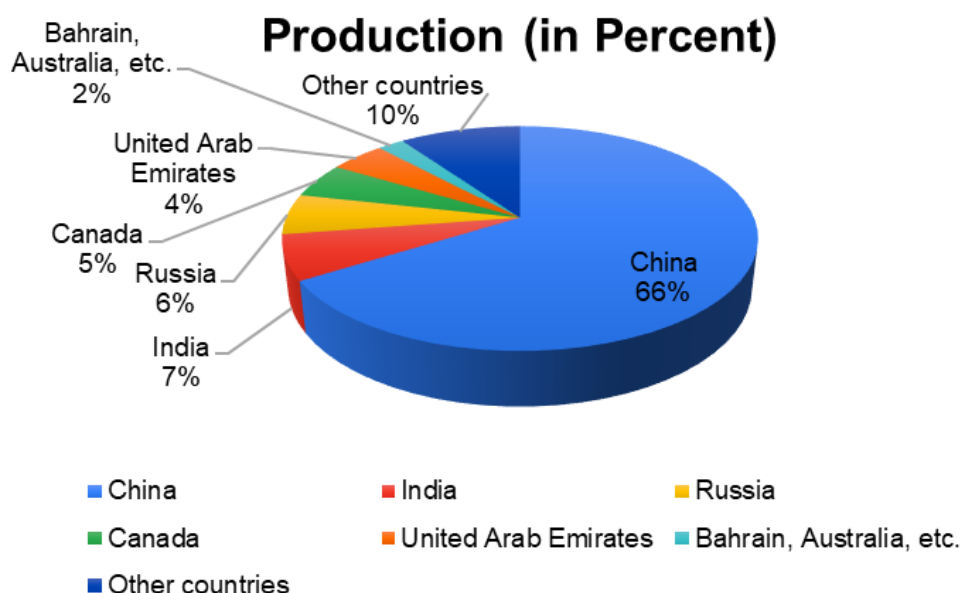


Figure 1: World's Largest Aluminium Producing Countries in year 2024 (Wikipedia contributors : Aluminium).

The pie chart in Figure 1 illustrates the distribution of aluminium production among different countries. In 2024, China was the largest aluminium producer with an output of 43,000 thousand tons (66%), followed by India with 4,200 thousand tons (7%), Russia with 3,800 thousand tons (6%), and Canada with 3,300 thousand tons (5%). The United Arab Emirates contributed 4%, Bahrain, Australia, etc. contributed 2%, while the remaining 10% was produced by other countries, bringing the total global production to 72,000 thousand tons. This highlights China's significant dominance in aluminium production compared to other nations. Furthermore, to meet increasing demands and overcome the limitations of conventional materials, composite materials have emerged as a promising alternative (National Minerals Information Center). Composite materials are engineered and developed to address technological challenges across a wide range of applications, including automotive components, sports equipment, aerospace parts, consumer products, and marine structures. Their growing use is driven by superior performance characteristics, functional advantages, and the ability to produce lightweight components (Chawla, 1998), (Mazumdar, 2001).

Aluminium matrix composites (AMCs), with their enhanced strength, increased stiffness, reduced density, and superior abrasion and wear resistance, provide a better alternative to conventional materials for structural, non-structural, and functional applications (Surappa, 2003). While micro-sized reinforcements are commonly used in aluminium matrix composites (AMCs), advancements in nanoscience have enabled the incorporation of nanoscale reinforcements, giving rise to a new class of materials known as Metal Matrix Nanocomposites (MMNCs) (Choi & Awaji, 2003).

An study proposed the concept of “nanocomposites,” a novel material design approach in which nanoscale particles are dispersed as a second phase within a matrix to enhance the various properties of composite materials. Nanosized reinforcements can significantly enhance mechanical strength, creep resistance at elevated temperatures, machinability, and fatigue life, all while maintaining ductility. These improvements in metal matrix composites (MMCs) are attributed to factors such as hardening mechanisms, fine particle size, uniform particle distribution, optimal inter-particle spacing, and thermal stability at high temperatures (Cao¹, 2008), (Cao², 2008), (Cao³, 2008).

Hybrid composites are engineered by combining two or more types of reinforcements such as fibers, short fibers, particulates, whiskers, and nanotubes to achieve tailored mechanical and functional properties. Hybrid composites can incorporate different reinforcement materials such as (SiC, Al₂O₃), (Graphite, SiC), and (Graphite, Al₂O₃). For example, car engine blocks often use graphite and alumina particulates as reinforcements to enhance performance (Wong *et al.*, 2006), (Ge & Gu, 2001), (Zhang *et al.*, 2006). Hybrid metal matrix composites exhibit improved mechanical properties due to reduced meniscus penetration defects and minimization of intermetallic compounds formation at the interfaces, resulting from an increased interfacial area (Sureshbabu *et al.*, 2007). Globally, a limited number of studies are available on aluminium (Al)-based hybrid composites. Only a few research studies investigate aluminium-based hybrid composites, particularly focusing on reinforced Al and Al alloys with hybrid compositions.

Hybrid Aluminium Metal Matrix Composites (HAMMCs) have gained significant attention over decades of research for their exceptional mechanical strength, thermal stability, and wear resistance. Stir casting has emerged as the most widely used fabrication method due to its cost-effectiveness and suitability for large-scale production. The incorporation of ceramic, agro-waste, and nanostructured reinforcements such as SiC, B₄C, RHA, Gr, and MWCNTs has led to marked improvements in hardness, tensile strength, and tribological properties. Hybridization enhances load transfer, refines microstructure, ensures uniform particle distribution, and reduces porosity. The use of sustainable and high-performance fillers reflects a growing emphasis on eco-efficient material design, enabling the development of application-specific composites for advanced industrial needs.

2. Brief Overview of Fabrication Techniques for Metal Matrix Composites (MMCs)

Metal Matrix Composites (MMCs) are typically produced by incorporating reinforcement materials into a metallic matrix. Several fabrication techniques have been developed for this purpose, including powder metallurgy, spray atomization, co-deposition, stir casting, squeeze casting, and plasma spraying (Ge *et al.*, 2001). Another study examined the influence of fly ash reinforcement on the flexural behavior and microstructure of aluminum matrix composites (AMCs) produced via stir casting. Fly ash, a low-cost aluminosilicate waste from thermal power plants, was incorporated at 10-40 wt% to enhance mechanical performance and sustainability. Results showed that flexural strength increased significantly with reinforcement up to 30 wt%, achieving 314.30 N/mm² compared to 89.19 N/mm² for pure aluminum, due to improved load transfer and interfacial bonding. However, strength declined beyond 30 wt% because of particle clustering and porosity. The flexural modulus peaked at 10 wt% (25,807.11 N/mm²), as excessive reinforcement reduced ductility. Microstructural analysis confirmed uniform particle dispersion and strong bonding at moderate loadings, while higher fractions led to agglomeration. The study concludes that fly ash is an effective, eco-friendly reinforcement for lightweight aluminum composites, suitable for automotive and structural applications (Emekwisia *et al.*, 2024).

Another researcher investigated the effect of silicon carbide (SiC) reinforcement and artificial aging on the mechanical and microstructural properties of Al6061-based metal matrix composites (MMCs) produced via two-stage stir casting. SiC particles of 35–40 μm were added in 2–6 wt.%, and samples were solution-treated at 558°C for 2 hours, quenched in water, and artificially aged at 100°C, 150°C, and 200°C. Hardness increased by 20–40% in as-cast composites compared to the unreinforced alloy, and maximum hardness improvement of up to 145% was recorded for 6 wt.% SiC aged at 100°C. The ultimate tensile strength (UTS) improved by 10–15% in as-cast and 40–70% after aging, reaching its peak at 6 wt.% SiC and 100°C aging. SEM analysis showed fine, uniform dimples and mixed-mode fracture behavior with increasing SiC content. The study confirmed that low-temperature aging and 6 wt.% SiC reinforcement optimize hardness and strength in Al6061-SiC composites (Shankar *et al.*, 2017).

The effect of sintering temperature and graphene content investigated on the structural and mechanical behavior of aluminum matrix composites (AMCs) fabricated via powder metallurgy. Graphene synthesized through Hummer's method was incorporated into aluminum at 0.1–0.5 wt.% and sintered between 550°C and 650°C under argon. XRD confirmed phase purity, while SEM revealed dense microstructures with reduced porosity at higher sintering temperatures. Density, hardness, and compressive strength increased with both rising sintering temperature and graphene content, achieving optimal results at 0.5 wt.% graphene and 600–650°C. Hardness improved from 27.7 HV (at 550°C) to 28.4 HV (at 650°C). Maximum densification occurred around 600°C, beyond which improvement was negligible. Compressive strength increased consistently due to graphene's high stiffness and load-transfer efficiency. Limited Al_4C_3 formation was detected at 650°C but did not significantly impair performance. The study concludes that graphene reinforcement enhanced mechanical properties, producing lightweight, high-strength aluminum composites suitable for advanced engineering applications (Garg *et al.*, 2016).

In summary, the studies confirm that fabrication method, reinforcement content, and processing temperature critically influence MMC performance. Stir casting ensures cost-effective uniform dispersion, while powder metallurgy enhances densification and strength. Optimized parameters yield lightweight, durable, and high-strength aluminum composites, making them promising materials for modern structural and automotive applications.

The above Table 1 shows a brief classification of the methods used for MMC fabrication, including solid-state, liquid-state, semi-solid, vapor-phase, and in-situ techniques, each offering distinct advantages for tailoring composite structure and properties.

2.1 Liquid Phase Processing Techniques

In these methods, the reinforcement is introduced into the matrix while the metal is in its molten (liquid) state. The composite is then shaped using conventional casting processes by pouring the molten mixture into molds of desired geometry. Common liquid-state techniques include:

- Stir Casting
- Compo Casting
- Squeeze Casting

• Stir Casting

Stir casting is widely regarded as one of the most effective and economical methods for producing Aluminium Metal Matrix Composites (AMMCs). In this process, reinforcement particles are mechanically stirred into molten aluminium, followed by casting into the desired shape (Panwar *et al.*,

2018). The success of this technique largely depends on several factors including the wettability of the reinforcements, chemical stability, and uniform dispersion of particles in the melt. The method was first employed in 1968 by S. Ray, who successfully stirred alumina ceramic particles into molten aluminium alloy using a mechanical stirrer (Sharma *et al.*, 2017). Stir casting is especially promising for producing near-net-shape components at a relatively low cost, making it a preferred method in industrial applications.

Table 1: Overview of Metal Matrix Composite (MMC) Fabrication Methods (Wikipedia contributors: Metal matrix composite), (Azpitarte and Knez, 2018), (He *et al.*, 2009).

Category	Method
Solid-State Methods	Powder Metallurgy
	Foil Diffusion Bonding
	Hot Pressing
	Friction Stir Welding (FSW)
Liquid-State Methods	Stir Casting
	Electroplating / Electroforming
	Pressure Infiltration
	Squeeze Casting
	Spray Deposition
	Reactive Processing
Semi-Solid-State Method	Semi-Solid Powder Processing
Vapor-Phase Method	Physical Vapor Deposition (PVD)
	Chemical Vapor Deposition (CVD)
In-Situ Fabrication	Directional Solidification
	Vapor Phase Infiltration (VPI)

2.2 Solid Phase Processing Techniques

These involve the fabrication of composites without melting the base metal. Instead, reinforcement particles are blended with metal powders and then consolidated using mechanical and thermal methods. Key solid-state fabrication techniques include:

- Friction Stir Processing (FSP)
- Powder Metallurgy (PM)
- High Energy Ball Milling

Among all these, stir casting and powder metallurgy are the most widely adopted due to their process flexibility, cost-efficiency, and suitability for both single and hybrid reinforcement systems (He *et al.*, 2009), (Panwar *et al.*, 2018).

- **Powder Metallurgy**

Powder metallurgy involves mixing fine powders of matrix and reinforcement materials, compacting them into a specific shape, and then subjecting the compact to sintering at elevated temperatures under a controlled atmosphere to achieve bonding (Sharma *et al.*, 2017). The process demands uniform dispersion of the reinforcement within the matrix to ensure a robust and consistent microstructure (Sharma *et al.*, 2014). Traditional powder metallurgy includes steps such as cold

pressing, sintering, and optionally plastic deformation methods like forging or extrusion. In some approaches, the green compact (unsintered part) is sintered first, followed by cold working to refine its properties (Torralba *et al.*, 2017).

Table 2 presents a comparison of different fabrication techniques used for producing Aluminium Metal Matrix Composites (AMMCs). The table outlines various fabrication techniques employed in the development of Aluminium Metal Matrix Composites (AMMCs), comparing their advantages, limitations, and key research references. Among these methods such as Friction Stir Processing (FSP), Powder Metallurgy (PM), Gravity Die Casting, Semi-Solid Densification, and Ablation Casting. Stir Casting stands out as the most prominently used and widely accepted fabrication technique.

Table 2: Comparative Analysis of Fabrication

S. No.	Fabrication Method	Advantages	Challenges	References
1	Stir Casting	• Economical • Mass production • Handles various reinforcements	• Particle clustering • Porosity • Sensitive controls to stirring/temp	(Kaczmar <i>et al.</i> , 2000), (James & Annamalai, 2018), (Rajmohan <i>et al.</i> , 2013), (Nathan <i>et al.</i> , 2021), (Sarada <i>et al.</i> , 2015), (Ravindran <i>et al.</i> , 2019)
2	Friction Stir Processing (FSP)	• No melting, fewer defects • High surface hardness • Refined microstructure	• Limited to surface (unless repeated) • Equipment intensive	(Srivastava <i>et al.</i> , 2014), (Arora <i>et al.</i> , 2012), (Ramesh & Murugan, 2013)
3	Powder Metallurgy (PM)	• Uniform nano/micro distribution • Enables hybridization • High precision	• Time intensive • Porosity if sintering is poor	(Deepak <i>et al.</i> , 2013), (Guo & Tsao, 2000), (Akhlaghi & Mahdavi, 2011)
4	Gravity Die Casting	• Better than sand casting • Good for simple Al parts	• Shape limitations • Risk of surface porosity	(Iacob <i>et al.</i> , 2013)
5	Semi-Solid Powder Densification	• Better mechanical and tribological behavior • Fine-tuning of reinforcement	• Requires precise control of phase state and temperature	(Achutha <i>et al.</i> , 2008)
6	Ablation Casting	• High cooling rates • Grain refinement • Aerospace-grade properties	• Complex setup • Less common in conventional labs	(Weiss <i>et al.</i> , 2011)

Among all the following techniques, stir casting is the most prominently used technique, as indicated by the highest number of supporting studies (Kaczmar *et al.*, 2000), (Weiss *et al.*, 2011). Researchers widely prefer it due to its low cost, process simplicity, and suitability for large-scale production. It effectively accommodates various reinforcements like SiC, Al₂O₃, B₄C, and graphite.

Although other methods like Friction Stir Processing and Powder Metallurgy offer refined microstructures or nano-scale dispersion, they are more equipment-intensive or limited to surface

modifications. In contrast, stir casting enables full-volume reinforcement and near-net shape fabrication, making it ideal for both research and industrial applications. Therefore, it remains the most dominant and versatile method for AMMC fabrication across recent literature.

3. Next-Generation Aluminium Matrix Composites: A Review of Reinforcement Materials, Fabrication Techniques, and Application Prospects

Aluminium Matrix Composites (AMCs) and Metal Matrix Nanocomposites (MMNCs) have emerged as vital materials in modern engineering due to their superior strength-to-weight ratio, enhanced wear resistance, and adaptability to a diverse range of reinforcement materials. In pursuit of advanced composites with optimized mechanical and tribological properties, researchers have investigated the integration of various reinforcements ranging from conventional ceramics, such as SiC, TiC, and TiB₂, to agro-waste-based fillers like rice husk ash (RHA), and nano-sized reinforcements, including Al₂O₃. The choice of reinforcement, fabrication technique, and distribution quality directly affects the structural performance, wear behavior, and sustainability of these composites. Techniques such as powder metallurgy, stir casting, and in situ synthesis have been employed to enhance the bonding and dispersion of reinforcements, while simultaneously reducing porosity and agglomeration. The reviewed studies provide a comprehensive view of the advances and challenges in the development of next-generation AMCs for automotive, aerospace, and defense applications. Earlier studies also directed to focus on advanced surface modifications, hybrid reinforcement designs, and long-term durability studies to enhance industrial adoption (Kumar *et al.*, 2025). Several researchers note that further investigation is still required, especially in achieving uniform nanoparticle dispersion, effective reinforcement pre-treatment, and the scalable fabrication of hybrid composites. Continued focus on eco-friendly reinforcements and multi-objective optimization is essential to balance cost, strength, and sustainability. Overall, the literature supports ongoing efforts toward lightweight, high-strength, and sustainable aluminum composites for advanced structural applications (Kalra *et al.*, 2018), (Gaurav *et al.*, 2024).

A study explored the microstructural, mechanical, and tribological behavior of Aluminium matrix composites (AMCs) reinforced with rice husk ash (RHA) and silicon carbide (SiC). The composites were produced using the powder metallurgy (PM) method with varying RHA contents of 0, 5, 10, and 15 wt%. The study found that mechanical properties, particularly hardness, improved with increasing RHA up to 10 wt%, beyond which agglomeration affected uniformity and performance. Wear resistance and coefficient of friction were evaluated against a steel counterface, revealing that RHA and SiC reinforcements reduced wear and improved frictional behavior. Microstructural analysis confirmed a homogeneous particle dispersion, except at higher RHA content (15%), where slight clustering was observed. This research highlights the sustainability potential of agro-waste (RHA) in developing cost-effective and performance-enhancing metal matrix composites. It also emphasizes the benefit of hybrid reinforcement combining synthetic (SiC) and agricultural (RHA) fillers to optimize both mechanical and tribological properties (Shaikh *et al.*, 2019). Researchers examined the tribological behavior of AA7075 Aluminium matrix composites reinforced with titanium carbide (TiC), produced via the powder metallurgy (PM) technique.

In-depth analysis of the synthesis, corrosion behavior, and industrial applications of metal matrix nanocomposites (MMNCs), focusing primarily on iron-based systems fabricated via powder metallurgy. The study identifies powder metallurgy as the most suitable technique for high-melting-point metals, ensuring uniform reinforcement dispersion and superior interfacial bonding. Among Fe–Al₂O₃ nanocomposites, reactive sintering between 900–1100°C leads to the formation of iron aluminate

(FeAl₂O₄), which enhances both mechanical integrity and corrosion resistance. Electrochemical testing revealed that alumina reinforcement and cobalt oxide (CoO) doping significantly reduce corrosion current density, achieving up to 99.99% corrosion inhibition through the formation of stable passivating films. Microstructural analyses (XRD, SEM, EDAX) confirmed nanoscale reinforcement distribution and protective oxide layer formation. The authors conclude that controlled sintering conditions and dopant optimization are crucial for maximizing corrosion performance, positioning Fe-based MMNCs as promising candidates for advanced structural and industrial applications (Kumar *et al.*, 2019).

The study aimed to enhance the wear resistance of Aluminium for applications in aerospace, automotive, and defense industries. Sliding wear tests were conducted using Taguchi's L9 orthogonal array to identify the optimal process parameters for minimizing wear rate. Results showed that sliding velocity and reinforcement content significantly influenced wear behavior. The wear mechanisms were primarily abrasion and adhesion, and composites with TiC reinforcement exhibited improved resistance. The PM process was highlighted as a cost-effective and efficient method for producing high-quality metal composites. The study concludes by recommending further exploration into hybrid reinforcements and their mechanical/metallurgical properties to develop advanced composite materials (Saravanan *et al.*, 2018). Another study, investigated the microstructure and wear behavior of Al6061 metal matrix composites (MMCs) reinforced with titanium diboride (TiB₂) particles using the stir casting technique. The study emphasized that the incorporation of ceramic particulates like TiB₂ can substantially improve mechanical integrity and wear resistance by refining the microstructure and enhancing interfacial bonding. The research focused on optimizing processing parameters to ensure uniform distribution of reinforcements and minimize porosity. Results exhibit a significant improvement in wear resistance and hardness with increasing TiB₂ content, attributed to the formation of a hard ceramic network that resists plastic deformation and abrasive wear. The composites showed a notable reduction in wear rate compared to unreinforced Al6061 alloy, with wear mechanisms shifting from adhesive to abrasive as TiB₂ concentration increased. Microstructural analysis revealed fine, uniformly distributed TiB₂ particles leading to increased load-bearing capability and improved fracture resistance. The study also highlighted the energy efficiency and material savings potential of these composites in applications such as aerospace and automotive components, where weight reduction and durability are critical. The findings supported the use of stir casting as a cost-effective and scalable fabrication route for advanced MMCs. The paper concluded by recommending further exploration of hybrid reinforcements and heat treatment processes to tailor properties for specific engineering applications (Suresh & Moorthi, 2013). Comprehensive investigation carried out into Aluminium matrix nanocomposites (MMNCs) by reinforcing Al 7075 alloy with nano-sized Al₂O₃ particles using the double stir casting technique. The research demonstrated that the addition of nano Al₂O₃ up to 5 wt.% led to progressive improvements in tensile strength, hardness, and wear resistance, owing to homogeneous dispersion and enhanced interfacial bonding. However, beyond 5 wt.%, particularly at 7 wt.%, the mechanical performance declined due to nanoparticle agglomeration and increased porosity, highlighting the critical role of dispersion quality in MMNCs. Results indicated that wear rate decreased consistently with increasing nanoparticle content under higher loading conditions, attributed to the formation of a stable tribolayer and the higher hardness of the composite. Microstructural analysis confirmed a refined grain structure and uniform nanoparticle distribution up to optimal loading, beyond which clustering degraded composite integrity. The study underscored the superior performance of MMNCs over conventional MMCs, especially in applications demanding high strength-to-weight ratios and improved surface durability, such as in aerospace, defense, and

automotive components. The paper concluded with a recommendation for further exploration of nanoparticle dispersion methods and hybrid nano-reinforcements to optimize mechanical and tribological synergy in future materials (Raturi *et al.*, 2017).

In a Study investigated the fabrication and mechanical behavior of graphite particulate-reinforced Aluminium matrix composites (AMMCs) using the stir casting method. The study aimed to evaluate the influence of graphite mass fraction (0-12 wt.%) on the composite's structural integrity and mechanical performance, given the potential of particulate-reinforced AMMCs to replace conventional materials in lightweight engineering applications. The results showed that increasing graphite content led to a gradual decrease in hardness and tensile strength, primarily due to poor interfacial bonding and non-uniform dispersion of graphite particles. The inherent brittleness of graphite further exacerbated the degradation of mechanical properties, especially at higher reinforcement levels. Microstructural analysis confirmed the non-homogeneous distribution and clustering of graphite, which introduced stress concentrators and weakened the matrix-particle interface. Despite these drawbacks, the study provided important insights into the limitations of using graphite as a reinforcement in Aluminium matrices, suggesting that its lubricating properties may benefit specific tribological applications but at the cost of load-bearing capacity (Mohanavel *et al.*, 2018).

The *in-situ* formation of zirconium diboride (ZrB_2) particulates within an AA7075 Aluminium matrix to enhance the composite's mechanical properties. The study aimed to overcome the limitations of conventional stir casting methods such as poor wettability and weak interfacial bonding by synthesizing ZrB_2 reinforcements directly within the melt through the reaction of K_2ZrF_6 and KBF_4 salts at 850 °C. This approach led to a homogeneous distribution of particulates and eliminated the formation of undesirable phases, ensuring the chemical purity of the composite. Findings revealed that *in situ* ZrB_2 particulates significantly refined the Aluminium grain structure and improved interfacial bonding. Morphological analysis identified various particulate shapes, including spherical, cylindrical, and hexagonal forms. Mechanical characterization showed a notable increase in microhardness and ultimate tensile strength with rising ZrB_2 content; however, a corresponding decrease in ductility (elongation) was observed. Techniques such as XRD, SEM, EBSD, and TEM confirmed the fine dispersion and structural integrity of the reinforcements. The study concluded that *in situ* synthesis is a superior method for producing high-performance AA7075-based composites, offering improved mechanical behavior without compromising material purity (Selvam & Dinaharan, 2017).

A study investigated the incorporation of mussel shell powder (MSP), an aquaculture waste rich in CaO, as a sustainable reinforcement for Al-Mg-Si aluminum composites. Using the stir casting method, MSP was added in varying proportions (0-15 wt%) to enhance the alloy's wear resistance. Microstructural analysis revealed uniform dispersion and strong interfacial bonding of MSP particles, particularly at 15 wt%, aided by magnesium addition. XRF confirmed the presence of hard ceramic oxides (CaO , SiO_2 , Al_2O_3), improving matrix hardness and wear resistance. Pin-on-disc wear tests demonstrated a significant reduction in wear rate, reaching $3.182 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$ at 15 wt% MSP. Enhanced performance was attributed to the formation of a protective transfer layer and solid lubricant behavior of CaO phases. The study concludes that MSP effectively improves tribological properties, offering an eco-friendly, low-cost reinforcement for automotive and industrial applications while promoting sustainable waste utilization (Mu'azu *et al.*, 2022).

The effect of silicon carbide (SiC) nanoparticle reinforcement studied on the structural and mechanical behavior of aluminum metal matrix composites (Al-MMCs) fabricated through mechanical alloying. Pure aluminum powder was mixed with 0-15 wt% SiC nanoparticles via high-energy ball milling, compacted, sintered at 495°C, and rolled to improve density. SEM and XRD analyses revealed

refined grains and uniform SiC dispersion up to 10 wt%, beyond which clustering occurred. Mechanical results showed significant improvement in yield (54.3-157.5 MPa) and tensile strength (85.4-187.5 MPa), hardness (23-106 BHN), and modulus (77-106 GPa) with increasing SiC. However, ductility decreased (27.8%-7.3%) due to brittleness. Optimum performance was achieved at 7.5-10 wt% SiC, balancing strength and toughness. The study concludes that nano-SiC effectively enhances aluminum's mechanical properties, making it promising for aerospace and automotive applications requiring high strength-to-weight ratios Najmeddin ([Arab, 2020](#)).

Developed aluminum matrix composites (Al6063/CFBP) reinforced with carbonized fish bone powder (CFBP) to enhance mechanical strength, corrosion resistance, and electrical insulation using sustainable bio-waste. The composites were fabricated via stir casting with 0-15 wt% CFBP, ensuring uniform dispersion through controlled stirring and preheating. Results showed that CFBP significantly improved mechanical and corrosion properties. Hardness increased from 55.3 to 67.48 kgf/mm², and tensile strength rose from 138.4 to 146.32 N/mm² at 15% reinforcement. Corrosion tests indicated a sharp decline in corrosion rate (0.4828 mm/yr) and current density due to passive film formation on the alloy surface. Electrical resistivity increased with higher CFBP content, confirming its insulating effect. SEM analysis revealed refined grains, strong interfacial bonding, and minimal porosity. Overall, CFBP proved to be an eco-friendly, low-cost reinforcement that enhances mechanical and corrosion performance while adding electrical insulation potential to aluminum composites ([Fayomi et al., 2020](#)).

The literature consistently highlights that reinforcement type, size, and dispersion critically influence the mechanical and tribological properties of Aluminium matrix composites. Agro-waste (RHA) with SiC improves hardness and wear resistance, while TiC, TiB₂, and in situ ZrB₂ enhance strength and microstructure. Nano-Al₂O₃ offers superior performance but is limited by agglomeration issues, and graphite shows poor bonding despite tribological potential. Overall, effective reinforcement selection, processing optimization, and dispersion control are key. Hybrid and in situ strategies show strong potential, with future research needed on synergistic combinations and post-processing to meet advanced application demands. Additionally, Studies on aluminum and iron-based metal matrix composites (MMCs) highlight that reinforcement type, content, and fabrication method critically influence mechanical, tribological, corrosion, and functional properties. Incorporation of ceramic nanoparticles, carbon-based nanomaterials, and sustainable waste-derived reinforcements combined with stir casting, powder metallurgy, or mechanical alloying achieves uniform dispersion, grain refinement, and strong interfacial bonding.

4. Influence of Boron Carbide Particle Size, Content, and Dispersion Techniques on the Microstructure and Mechanical Behavior of Aluminium Matrix Composites

Aluminium matrix composites (AMCs) reinforced with boron carbide (B₄C) particles have gained significant attention in recent years due to their superior mechanical and tribological properties, making them suitable for high-performance applications in aerospace, automotive, and defense industries. The effectiveness of B₄C as a reinforcement depends heavily on factors such as particle size, volume fraction, dispersion uniformity, and fabrication technique. Researchers have explored various strategies to optimize these parameters. With advancements in science and technology, particularly in nanotechnology, boron has gained significant attention across various industrial sectors. In contrast, other group members continue to have limited commercial value. Nonetheless, certain compounds of boron and Aluminium are indispensable in modern technology and are widely utilized across the globe ([Massey & Hosmane, 2024](#)).

Initially explored the influence of boron carbide (B₄C) particle size and spatial distribution on the mechanical behavior of Aluminium metal matrix composites (Al MMCs), specifically Al 7075/B₄C systems. The study synthesized composites with three distinct B₄C particle sizes and examined their microstructure and mechanical response. It was found that finer B₄C particles increased yield and fracture strength but often exhibited agglomeration, leading to non-uniform distribution. In contrast, coarser particles displayed better homogeneity but contributed less to mechanical enhancement. The results showed that particle size and spatial distribution directly affect fracture mechanisms, suggesting that interfacial bonding and stress transfer are heavily size-dependent. This underscores the critical role of reinforcement characteristics in MMC design. Despite advancements, the authors highlighted that fundamental understanding remains limited regarding how reinforcement morphology and dispersion patterns influence mechanical properties such as toughness, ductility, and strength (Wu *et al.*, 2016). Many researchers studied the microstructure and mechanical behavior of AA2024 Aluminium matrix composites reinforced with B₄C particles, focusing on the effect of varying B₄C content. The composites were fabricated using plasma-activated sintering (PAS), which enabled the production of nearly fully dense materials. The incorporation of B₄C resulted in increased hardness and compressive yield strength, attributed to the stiff reinforcement and refined microstructure. At lower reinforcement levels, B₄C particles were uniformly distributed in a network-like structure. However, higher B₄C contents led to particle agglomeration, adversely affecting the load transfer efficiency and limiting further improvements in mechanical performance. The study confirms that while B₄C reinforcement can significantly enhance mechanical properties, excessive content may deteriorate the composite's integrity due to interfacial issues and clustering (Luo *et al.*, 2017). A study investigated the microstructure and sliding wear behavior of AA2124 Aluminium alloy matrix composites reinforced with micro- and nano-sized boron carbide (B₄C) particles. The composites were produced via stir casting, a cost-effective method suitable for Aluminium matrix composites (AMCs). To enhance particle wettability and dispersion, B₄C was preheated and K₂TiF₆ was added. Microstructural analysis revealed refined dendritic structures and uniform particle distribution, with no detectable interfacial reactions between Aluminium and B₄C. Incorporating nano-sized B₄C led to grain refinement, increased microhardness, and improved wear resistance compared to micron-sized reinforcements. The study demonstrates that nano-B₄C reinforcement is more effective in enhancing the mechanical and tribological properties of AMCs without significantly compromising ductility, highlighting their potential for aerospace and structural applications (Esther *et al.*, 2019). The recent studies demonstrate that the mechanical and wear properties of Aluminium matrix composites are highly dependent on the size, content, and dispersion of B₄C reinforcements. Fine and nano-sized particles improve strength and wear resistance but may lead to agglomeration if not well dispersed. Optimal reinforcement content and processing techniques, such as plasma sintering and stir casting with flux treatment, are crucial for uniform distribution and strong interfacial bonding. These findings highlight the need for precise control of reinforcement parameters to develop high-performance, lightweight AMCs for advanced structural and tribological applications.

5. Influence on the Properties of Hybrid Aluminium Matrix Composites: A Review

Hybrid Aluminium Metal Matrix Composites (HAMMCs) have emerged as a promising class of advanced materials, combining the lightweight nature of aluminium with the superior properties imparted by multiple reinforcements. Their high strength-to-weight ratio, excellent wear and corrosion resistance, and improved thermal and mechanical behavior make them ideal for aerospace, automotive, and structural applications. Stir casting is the most widely used fabrication method due to its simplicity,

cost-effectiveness, and ability to incorporate a variety of reinforcements uniformly. Reinforcements such as silicon carbide (SiC), boron carbide (B₄C), Aluminium oxide (Al₂O₃), titanium diboride (TiB₂), graphite, multi-walled carbon nanotubes (MWCNTs), and agro-waste-based materials like rice husk ash (RHA) significantly influence the hardness, damping behavior, and corrosion resistance of HAMMCs. The use of hybrid, in-situ, and nano-reinforcements reflects a shift toward more sustainable, high-performance, and eco-efficient composite designs. Additionally, innovative methods such as two-step mixing and preheating treatments further enhance particle distribution and matrix bonding. This review discusses how the selection of reinforcements and processing techniques impacts the structural integrity and performance of HAMMCs, while highlighting future directions focused on fatigue behavior, lifecycle analysis, and industrial scalability.

A study examined the influence of alumina (Al₂O₃) and graphite (Gr) reinforcements on the microstructure and flexural strength of AA6063 aluminum alloy-based hybrid metal matrix composites (HMMCs) produced via stir casting. Al₂O₃ (20 µm) was incorporated at 0–12 wt.% with a constant 1 wt.% graphite. Microstructural and mechanical analyses revealed that 6 wt.% Al₂O₃ yielded optimal results, exhibiting refined grains (70 µm), uniform particle distribution, and strong interfacial bonding. Flexural strength increased up to this composition due to effective load transfer and grain refinement, while higher reinforcement levels (≥9 wt.%) caused particle agglomeration, porosity, and brittleness, leading to strength deterioration. Fractographic studies confirmed ductile fracture behavior at 6 wt.% and brittle failure beyond this limit. The study concludes that the AA6063-6% Al₂O₃-1% Gr composite offers the best balance of strength and ductility, highlighting the importance of controlled reinforcement content and processing parameters for high-performance hybrid composites ([Saravanakumar and Sasikumar, 2018](#)).

Researchers developed HAMMCs by combining stir squeeze casting with ultrasonic stirring, utilizing scrap aluminium alloy wheels reinforced with nano-sized and micro-sized alumina. The dual processing achieved a refined microstructure, reduced porosity (3.41%), and superior particle dispersion. The optimal composite (E8) reached 186 MPa tensile strength and 539 MPa compressive strength, while hardness peaked at 60 HRB due to strong particle-matrix bonding and dislocation resistance. Wear loss was minimized (0.004 g) owing to the formation of a mechanically mixed layer and stable oxide films ([Thiraviam et al., 2020](#)). In the previous study, synthesized Al 6061-based HAMMCs reinforced with SiC (15 vol%) and MWCNTs (0.5–1.0 vol%) via stir casting. The inclusion of MWCNTs led to a significant increase in Rockwell hardness, with the highest value recorded at 55 HRB. Tribologically, the composite demonstrated improved wear resistance and reduced friction due to the lubricating effect of MWCNTs and enhanced load sharing. This combination leveraged the strengths of both micro- and nano-reinforcements effectively ([Padmavathi & Ramakrishnan, 2014](#)). Another study, investigated the hybridization of SiC, Al₂O₃, and fly ash in Al 6061 via stir casting. The study found that increasing SiC and Al₂O₃ content improved tensile strength (up to 129 MPa) and hardness (peak at 64 BHN), while medium reinforcement content (7.5% each) yielded the best wear resistance. The observed improvement was due to efficient stress transfer and reinforcement dispersion. Impact strength, however, remained mostly unchanged, affirming the brittle nature of ceramic reinforcements ([Hima Gireesh et al., 2018](#)). Aluminium metal matrix composites with focused on AA6061 reinforced with SiC 2–6 wt% and ZrO₂ 3 wt% using stir casting. The combination provided a balanced improvement in properties: tensile strength rose to 384.4 MPa, hardness reached 95.5 BHN, and impact strength increased by 16%. The uniform distribution of reinforcements, confirmed through SEM and XRD, contributed to reduced porosity and enhanced interfacial bonding, critical to mechanical integrity ([Nathan et al., 2021](#)).

A study used stir casting to fabricate composites with Al 356 matrix reinforced with 10% SiC and varied mica content. The 3% mica composite exhibited the best mechanical behavior, achieving 150 MPa tensile strength and 115 HRB hardness. Mica's lubricating properties improved wear resistance through the formation of a stable mechanically mixed layer. However, increasing mica beyond 3% reduced mechanical performance due to clustering and porosity (Rajmohan *et al.*, 2013). Another study analyzed the effects of hybrid SiC + graphite reinforcement in Al 6063, showing that a 7.5%–7.5% combination delivered the highest tensile strength (200.32 MPa) and improved wear resistance. Graphite provided lubrication and stress relief, while SiC ensured matrix strengthening. The microstructure remained defect-free, and no significant ductility loss was reported demonstrating an effective hybrid strategy (Babu *et al.*, 2020). With reinforced LM25 alloy with activated carbon, mica, and their hybrid, fabricated via stir casting. The hybrid composite outperformed single-reinforced variants in hardness (29.03% higher than mica alone) and wear resistance (10% lower wear loss). Improved particle bonding and smoother wear tracks were attributed to effective process control and synergy between reinforcements (Sarada *et al.*, 2015). The fabricated HAMMCs using Al 6061 alloy with ZrO₂ (5%) and Al₂O₃ (5%) via stir casting. The composite showed significant enhancements in tensile strength 227.33 MPa, hardness 82.9 HRC, and wear resistance 41.85 µm wear depth under 150 N. Corrosion resistance also improved due to oxide layer formation, especially by Al₂O₃. Microstructural analysis revealed uniform reinforcement dispersion and minimal agglomeration, thanks to careful preheating and stirring practices (Bazzi *et al.*, 2013; James & Annamalai, 2018). Previously investigated the mechanical properties of AA 7075-based hybrid composites reinforced with boron carbide (B₄C) and rice husk ash (RHA) using the stir casting technique. The dual reinforcements significantly enhanced hardness, tensile, and compressive strength, with 5 wt% B₄C and optimal RHA yielding peak performance. This study demonstrated the synergistic strengthening effect of combining ceramic and agricultural reinforcements, addressing a critical research gap by exploring the unexplored hybridization of B₄C and RHA in AA 7075 composites. It highlighted the sustainability potential of RHA in advanced materials (Verma & Vettivel, 2018). The in-situ synthesis and wear behavior of TiB₂-reinforced AA2014 Aluminium matrix composites. The composites were fabricated through an exothermic salt reaction involving K₂TiF₆ and KBF₄ at 850°C, with reaction durations ranging from 15 to 45 minutes to control TiB₂ particle growth. The resulting in-situ composites exhibited significant grain refinement and improved wear resistance compared to unreinforced AA2014. The addition of TiB₂ not only enhanced hardness but also substantially reduced the coefficient of friction, making the material suitable for high-wear applications. Microstructural analysis confirmed the uniform dispersion of fine TiB₂ particles, contributing to the improved tribological performance. The study highlights the effectiveness of in-situ fabrication methods in producing clean particle-matrix interfaces, superior to those typically found in ex-situ techniques (Mallikarjuna *et al.*, 2011).

The microstructure and mechanical properties of hybrid Aluminium matrix composites (HAMMCs) based on 2024Al reinforced with silicon carbide (SiC) and graphite (Gr). The composites were fabricated using vacuum hot pressing followed by hot extrusion, aiming to improve bonding and control interface reactions. The study varied SiC (5-10%) and Gr (3-6%) contents to evaluate their influence on the composites' performance. Results showed that SiC significantly enhanced the aging hardening response due to its effect on precipitate formation, while Gr improved damping capacity but adversely affected strength. Both reinforcements reduced tensile strength and ductility, with ductile fracture observed at the matrix–particle interface. The findings emphasize the trade-off between mechanical strength and other functional properties in hybrid composites (Bin, 2016). For the

enhancement of AA2024 hybrid nanocomposites investigated by incorporating 4% SiC and 4% MWCNTs via a two-step stir casting process. The study addressed agglomeration and microporosity issues, achieving improved dispersion, microstructural uniformity, and defect reduction. The optimized composite exhibited superior properties: 330 MPa tensile strength, 10% elongation, 128 HV hardness, and enhanced corrosion resistance. MWCNTs boosted load transfer and crack-bridging, while SiC improved wear resistance and stiffness (Aruna *et al.*, 2024). Furthermore, the development of Al6061-based hybrid nanocomposite reinforced with nano-graphite and SiC using two-step stir casting. The optimized H3 composition achieved notable improvements: 42% higher yield strength, 19% higher tensile strength, and enhanced hardness and toughness. SEM analysis confirmed uniform dispersion, <1% porosity, and minimal agglomeration (Venkatesh *et al.*, 2024).

Hybrid Aluminium matrix composites (HAMMCs) are emerging as advanced materials that meet the increasing demand for lightweight, high-strength, and wear-resistant components, especially in aerospace, automotive, and structural sectors. Across all reviewed studies, stir casting consistently emerged as the preferred fabrication method due to its cost-effectiveness, versatility, and ability to accommodate diverse reinforcement types and sizes. The incorporation of traditional reinforcements like SiC, Al₂O₃, ZrO₂, and graphite, as well as nano and agro waste reinforcements such as MWCNTs and RHA, has shown to significantly enhance the composites' mechanical, tribological, and corrosion-resistance properties. Notably, two-step stir casting was effective in dispersing nano-reinforcements like MWCNTs and Graphene, minimizing agglomeration and improving load transfer and damping behavior. Agro-waste reinforcements such as RHA combined with B₄C offer a sustainable and cost effective solution, while in-situ formed TiB₂ ensures clean interfacial bonding, enhancing mechanical integrity. Hybrid aluminum matrix composites achieve optimal performance through controlled reinforcement type, content, and processing, which enhance strength, ductility, and microstructural uniformity, while excessive reinforcement can cause agglomeration and brittleness.

Conclusion

The fabrication of Metal Matrix Composites (MMCs), particularly Hybrid Aluminium Metal Matrix Composites (HAMMCs), has evolved through the application of both liquid-phase and solid-phase processing techniques. Among these, stir casting has consistently proven to be the most prominent and widely utilized method, owing to its simplicity, cost-efficiency, suitability for large-scale and versatile reinforcement integration. This technique effectively supports the uniform dispersion of diverse reinforcements such as SiC, Al₂O₃, ZrO₂, graphite, mica, and MWCNTs leading to marked improvements in tensile strength, hardness, and tribological performance across multiple studies.

The comparative evaluation of research from 2013 to 2025 reaffirms stir casting as the dominant fabrication route, with significant influence on composite integrity, microstructure, and mechanical behavior. Despite the emergence of advanced techniques like friction stir processing and powder metallurgy, their limitations in scalability and cost render them less favorable for industrial-scale implementation. Additionally, although the reviewed studies did not incorporate boron carbide (B₄C), extensive literature suggests that B₄C remains among the most effective reinforcements for aluminium matrices, offering unmatched hardness, thermal stability, and wear resistance. Thus, combining the proven capabilities of stir casting with high-performance reinforcements like B₄C presents a compelling direction for future HAMMC development in high-demand engineering applications.

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