A Review on the Progress and Challenges of Aluminum-Based Metal Matrix Composites: Fabrication and Applications

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Abstract - *Composite materials, distinguished by a matrix and reinforcing elements, play a crucial role in augmenting characteristics such as durability, rigidity, and resilience against wear. This paper explores the production of Aluminum-Based Metal Matrix Composites (MMCs), focusing on their fabrication processes, applications, and associated challenges. Numerous Aluminum MMCs have been developed, incorporating diverse reinforcements like borides, carbides, oxides, and nitrides. These reinforcements have led to stable structures within the composites, resulting in outstanding mechanical and wear properties. With a surge in materials science interest, Aluminum-based composites have gained prominence for their lightweight, high strength, and corrosion resistance. This paper reviews recent advancements in Aluminum MMCs, delving into the exploration of innovative materials, fabrication techniques, and their applications in aerospace and automotive industries.*

Key Words: **Composites, Aluminium, Reinforcement, Hybrid, Nano, Stir Casting, Powder Metallurgy**

1. INTRODUCTION

Composite materials are classified based on the type of matrix and reinforcement employed. In composites, a primary material serves as the matrix, while reinforcements are incorporated to improve characteristics like strength, stiffness, electrical conductivity, wear resistance and corrosion resistance. The reinforcements augment the matrix, bolstering its strength. The occurrence of wear is associated with relative movement between components and can impact the performance of various components. A Metal Matrix Composite (MMC) is a category of composite material wherein a metal acts as the matrix, fortified with another material to improve distinct properties. The reinforcement phase is typically in the form of particles, fibers, or whiskers embedded within the metal matrix. Metal matrix composites are designed to combine the advantageous properties of metals with the enhanced characteristics provided by the reinforcement.

Numerous Aluminum Metal Matrix Composites (MMCs) have been manufactured using diverse fabrication processes, taking into account different types of reinforcement particles such as borides, carbides, oxides, nitrides, and their combinations. The incorporation of these reinforcement particles has led to the formation of stable structures within the composites, resulting in Aluminum MMCs that exhibit outstanding mechanical and wear properties. In recent decades, the field of materials science has witnessed a surge in interest and research efforts directed towards the development of advanced materials with enhanced properties and functionalities. Among these materials, Aluminum-based composites have emerged as promising candidates for a wide range of applications, owing to their exceptional combination of lightweight, high strength, and corrosion resistance.

The demand for high-performance materials in industries such as aerospace, automotive, and construction has driven the exploration of novel approaches for enhancing the mechanical, thermal, and electrical properties of Aluminum and its alloys. Through the incorporation of reinforcing phases, such as ceramics, polymers, and carbon-based materials, Aluminum-based composites offer tailored solutions to meet specific engineering requirements. Over the past decade, there has been a substantial increase in research focused on Aluminum MMCs. These composite materials are increasingly replacing traditional metallic alloys, particularly in aerospace components like wings and fuselage, as well as automobile parts such as brake discs, drums, and pistons, offering enhanced performance at a comparatively lower production cost. This paper outlines the production methods of aluminium based composite materials along with their applications and the issues and challenges associated with them.

2. LITERATURE REVIEW

[1] Abideen Temitayo Oyewo et al., The current need for advanced engineering materials can be addressed through hybrid aluminum matrix composites (ABHCs), which find applications across various fields. Examination of the microstructure of hybrid composites with varying reinforcement percentages reveals a stable and uniformly distributed structure, particularly at lower percentages. Notably, the commonly employed fabrication methods for aluminum hybrid composites continue to be powder metallurgy and stir casting, with more intricate and precise methods being infrequently utilized. Furthermore, the study suggests that the introduction of solid reinforcing particles can enhance the strength of hybrid composites. Additionally, the mechanical properties of these alloys undergo significant improvement with the incorporation of ceramic particles such as silicon carbide, boron carbide, aluminum, and alumina. Solid lubricants, such as graphite (Gr), possessing commendable mechanical and wear characteristics, have the potential to act as secondary reinforcement. Consequently, emerging variations of aluminum-based hybrid composites derived from agricultural waste sources like rice husk ash, Bagasse Ash, groundnut shell particles, coconut shell ash, and fly ash, demonstrate potential in competing with primary reinforcements in the new generation of hybrid composites. Ultimately, the integration of novel composite materials like lithium aluminum alloy and fiber metal laminate (FML) holds promise for aeronautical applications.

[2] V.S.S. Venkatesh et al., This paper explores the synthesis of an aluminum composite reinforced with nano SiC particles using ultrasonically assisted stir casting and investigates the impact of SiC weight percentage on mechanical properties and fractography. Key findings reveal the uniform dispersion of SiC nanoparticles in various composites, except in the 2.0 wt% SiC composite, where an Al_2Cu intermetallic phase was identified. The composite reinforced with 1.5 wt% SiC particles demonstrated an 82.6% increase in ultimate tensile strength (U.T.S) and a 73.4% increase in hardness compared to unreinforced aluminum. The mathematical estimation of composite yield strength for all weight percentages of reinforcements closely aligns with experimental yield strength. Composite strengthening is primarily attributed to the thermal mismatch mechanism, followed by the Orowan strengthening mechanism and grain size refinement strengthening mechanism. Fractography analysis indicates a transition from ductile to brittle fracture with an increase in SiC nanoparticle addition. The composite reinforced with 1.5 wt% SiC nanoparticles exhibited superior U.T.S (431 MPa) and hardness (163 BHN) compared to other compositions. The study concludes by suggesting further research avenues, such as investigating the effect of ultrasonic frequency on mechanical behavior and exploring the impact of SiC nanoparticles on phase evaluation and mechanical properties in Al-nano SiC composites.

[3] Aniruddha V. Muley et al., This paper discusses the promising realm of Aluminium Matrix Composites (AMCs), which serve as lightweight engineering materials with exceptional properties. These composites find applications in various fields, including automobile, mining, aerospace, and defense. Recent technological advancements have facilitated the integration of nano-sized reinforcements into the aluminum matrix, leading to improved properties compared to their micro-sized counterparts. The utilization of hybrid reinforcements, involving different materials, imparts superior characteristics to aluminum matrix composites when compared to those reinforced with a single material. The paper presents an overview of the progress in the development of aluminum-based metal matrix composites, with a specific focus on nano and hybrid aluminum-based composites.

[4] Abuzer Açikgöz et al., This paper discusses the synthesis of innovative materials, often referred to as advanced or "high-tech" materials, by materials scientists using a range of synthesis approaches and methods. Metal matrix composites reinforced with nano particles are particularly promising for diverse applications due to their exceptional chemical, physical, and mechanical properties. In this investigation, nano Al_2O_3 was introduced as reinforcement in micro-sized iron powders at varying rates of 1, 2, 3, 4, and 5 wt%. The samples underwent preparation through mechanical alloying, pellet pressing, and sintering processes, followed by metallographic examinations involving grinding and polishing procedures. Despite a decrease in densities with an increase in the additive amount, a noteworthy outcome was the achievement of a 77% ratio of theoretical density to measured density in dry pressing. Hardness values displayed a linear increase corresponding to the augmentation in the additive amount, with the highest hardness value reaching 121.33 HV1 at the 5 wt% rate.

[5] Puneet Kumar Sonker et al., This paper discusses the utilization of powder metallurgy in the fabrication of Aluminium Hybrid Metal Matrix Composites (AHMCs) reinforced with 5%wt. Zinc (Zn) and varying percentages of Silicon Carbide (SiC-0, 5, 10, 15%wt.). The ensuing discussion offers a comprehensive overview of the hardness, tensile strength, and wear characteristics exhibited by AHMCs with different proportions of reinforcement elements. The powder metallurgy technique proves effective in synthesizing AHMCs. The incorporation of hybrid reinforcement, rather than relying on a single reinforcement, enhances hardness and wear resistance within the composite. Mechanical properties, encompassing both hardness and tensile strength, depend on the weight percentage of SiC content in the composite. The crucial factor influencing wear performance is the applied normal load, with friction coefficient values decreasing as the load is applied. Examination of composite surfaces during wear reveals the presence of adhesive and abrasive wear mechanisms.

[6] Muhammad Yasir Khalid et al., This paper discuss the current research efforts focused on enhancing aircraft performance through the exploration of lightweight materials with diverse combinations of nano reinforcements. Advanced Metal Matrix Composites (AMMCs) are redefining the landscape of aerospace applications. This extensive review delves into the evolving nature of next-generation AMMCs designed specifically for aerospace purposes, covering several key themes. These themes encompass the widespread effectiveness of AMMCs in various applications such as military, aerospace, automobiles, and structural uses, owing to their remarkable properties. The casting technique emerges as a preferred method for AMMC manufacturing, thanks to its simplicity, cost-effectiveness, and ability to uniformly disperse nano reinforcements for efficient mass production. The consistent incorporation of nano reinforcements proves instrumental in enhancing the mechanical, tribological, and microstructural properties of AMMC, regardless of the chosen manufacturing approach. However, challenges associated with reinforcement use, including improper mixing, agglomeration of particles, volume fraction issues, and crucible surface sedimentation, have been identified as factors diminishing the overall mechanical properties of AMMC. Notably, the integration of machine learning and algorithm-based approaches is gaining prominence in Metal Matrix Composites, enabling the successful prediction and control of various process parameters and subsequent mechanical properties.

[7] Yunhong Liang et al., This paper discusses the utilization of 3D printing to manufacture carbon fiber-reinforced aluminum composites with systematically arranged architectures of shear-induced aligned carbon fibers. The microstructures of both the printed and sintered samples were examined, and an exploration of the mechanical properties of the resulting composites was conducted. A bonding agent, resin, was utilized to bind carbon fibers and aluminum powder. During the 3D printing process, the spatial configuration of carbon fibers was permanently established within the aluminum matrix through shear-induced alignment. Consequently, the composites displayed an elongation of 0.82% for those with a parallel arrangement of aligned fibers and an impact toughness of 0.41 J/cm^2 for those with an orthogonal arrangement. These values were approximately 0.4 and 0.8 times higher, respectively, than those achieved with a random fiber arrangement.

[8] Kenneth Kanayo et al., In this investigation, the study delves into the structural characteristics, mechanical properties, and wear behavior of stir-cast Al-Mg-Si alloy-based composites reinforced with varying weight percentages of steel particles, a hybrid mix of steel and graphite, and SiC particles. The findings indicate an approximately 11% increase in the hardness of the composites as the steel particle content rises from 4 to 8 wt.%. Over the same range of steel concentration, the ultimate tensile strength demonstrates an upward trajectory with an increase in steel wt.%, surpassing the strength values of an 8 wt.% reinforced SiC by 3.2–24%. Specific strength and fracture toughness exhibit a similar trend concerning steel concentration, with strain to fracture experiencing only a slight decrease (less than 4%). These superior properties compared to the SiC-reinforced composite are attributed to enhanced grain refinement, interface bonding, and the inherent ductility of the steel particles. In the case of the 8 wt.% hybrid-reinforced composite compositions containing steel and graphite, all mechanical properties experience a slight decrease with an increase in graphite content, trailing the composite reinforced with 8 wt.% steel. Nevertheless, the wear rates are lowest for the hybrid reinforcement mix of steel and graphite, followed by those containing only steel, while the SiC-reinforced composite exhibits the highest wear susceptibility. However, abrasive wear remains the dominant observed wear mechanism in all the composites.

[9] Gowrishankar M C et al., The investigation concentrates on validating the actual weight percentage of reinforcements (Silicon carbide and Boron carbide) and assessing their impact on Aluminium alloy composites produced through stir casting. The resulting composites showcase a consistently distributed hardness across the entire cross-section. The acid solubility test indicates the presence of approximately 95% of reinforcements in the Aluminium composites. The existence and quantity of reinforcements significantly influence the properties of the Aluminium alloy, resulting in a notable increase of 50–80% in hardness and a 40–50% rise in tensile strength when compared to pure Aluminium alloy. The study concludes that stir casting proves to be an effective method for manufacturing Aluminium composites with enhanced properties.

[10] Awss A. Abdulrazaq The study explores the utilization of metal matrix composites (MMCs), specifically aluminum matrix composites (AMCs), in aerospace, automotive, and electronic applications. The primary focus is on developing cost-effective AMCs with improved mechanical and physical properties by employing natural base reinforcement materials through powder metallurgy technology. Date palm seeds and dolomite rocks were incorporated as reinforcements at various weights along with the aluminum matrix. The produced specimens underwent morphological and solid-phase characterization through X-ray diffraction, optical, and scanning microscopy. The microstructure of both reinforcement materials displayed a uniform particle size distribution, indicating the successful embedding of waste particles within the aluminum matrix. Mechanical tests revealed that the composite reinforced with date palm seeds demonstrated high hardness, reaching a peak of 50 HRV with 7.5% reinforcement, surpassing the dolomite-reinforced composite, which achieved 48.3 HRV at the same reinforcement level. In terms of compressive strength, the date palm seeds composite exhibited superior performance, withstanding 23.8 MPa at 7.5%, compared to the maximum compression resistance of 16.68 MPa for the dolomite-reinforced aluminum composite.

3. FABRICATION PROCESS

The creation of Al-based composites primarily involves the use of two widely employed processing techniques: solid-state and liquid metallurgy. The choice of a specific fabrication method is influenced by various factors, such as the selection of reinforcing materials and matrix, distribution capacity within the matrix, diameter, heat, and the mechanical and chemical interaction between the reinforcing particle and the matrix. [16, 17]. Figure 1 depicts the different trajectories that composites and hybrid composites may take throughout their development.

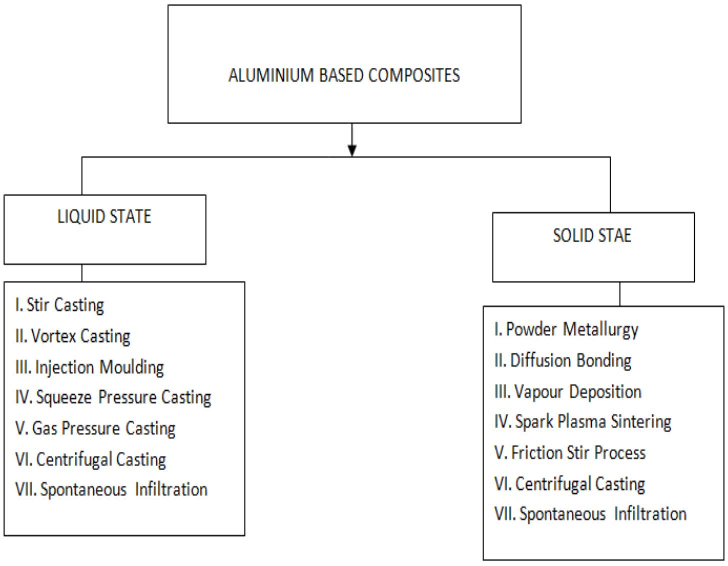

Fig -1: Processes for fabricating Aluminium and Hybrid composites based on Aluminium

In the domain of solid-state processing, commonly employed methods encompass powder metallurgy, diffusion bonding, and vapor deposition. Conversely, within the liquid-state process, Fig. 1 [12, 18] illustrates less commonly used techniques such as gas pressure infiltration, stir casting, squeeze casting, and others. According to existing literature, stir casting and powder metallurgy emerge as frequently employed approaches for manufacturing particle-reinforced metal matrix composites [19, 20]. Notably, stir casting stands out as the most viable method for creating particle-based composites in liquid-state processing due to its user-friendly nature and widespread commercial availability [21-23]. In their examination of Aluminum composite production methods, Abebe Emiru et al. [14] highlighted the significance of the stir casting technique. This method involves stirring a molten metal alloy to incorporate reinforcement before casting. Various process parameters, such as stirring duration, speed, and feed rate, can be adjusted to achieve desired microscopic investigations [19, 22]. Another effective liquid-state processing method is centrifugal casting. In this technique, molten metal is poured into a rotating mold, where centrifugal force propels the metal to spread across the inner mold surface. In the basic centrifugal casting method, centrifugal force induced by the spinning mold causes secondary particle phases to move radially from outer to inner regions concerning the axis of rotation. This movement follows a pattern transitioning from areas of higher density to lower density compared to the matrix density [15, 24].

Furthermore, with an increase in the combination of speed and stirring duration, the distribution of reinforcement in the fabricated composites becomes more homogeneous. In the powder processing stage, components are blended in fine powder form to achieve the desired shape. Subsequently, elevated temperature in a controlled environment is utilized to bond the materials together [11, 25, 26]. Achieving a robust microstructure in the produced composites requires a uniform mixture. For the successful fabrication of composites through the powder metallurgy process, three essential procedures must be completed: mixing, compaction, and extrusion [13, 16, 27, and 28]. The powder metallurgy technique places a greater emphasis on cold pressing after sintering and homogeneous material mixing than on hot pressing. Cold plastic work is often carried out, with the green component initially undergoing sintering [29]. A comparison of the most common fabrication procedures for the creation of Aluminum Based Hybrid Composites (ABHCs) is presented in Table 1.

Table -1: Contrasting various approaches for the fabrication of Aluminium Based Composites [15, 24, 30]

State	Process	Utilization	Details of Fabrication	Expense
Liquid	Stir Casting	Used for commercial purpose to create composites on Aluminium.	Controlling mixing duration and speed at a medium intensity. Pouring stage ensures proper wetting of the reinforcing components, while maintaining a controlled temperature before heating enhances the overall fabrication process.	Low/High
	Squeeze Casting	Suitable for the manufacture of aircraft parts.	Success relies on precise control of the die preheating temperature, pouring conditions, alloy temperature, and optimal pressure level and duration.	Moderate
	Gas Pressure Infiltration	Primarily appropriate for engine mounts, wheel assemblies, tubes, and rods.	Achieving desired properties hinges on meticulous control of the alloy's constituent elements, along with precise management of infiltration duration and temperature.	Low/Moderate

	In-situ Processing	Mainly used in the aerospace and defense industries.	Optimal outcomes are attained through careful control of reaction temperature, reaction speed, and the mass quantity of reactants, ensuring the synthesis of enhanced composite materials.	High
	Centrifugal casting	Rings, Compressors, Flangers	Molten metal is poured into a rotating mold with a coated bottom, incorporating a thin solvent reinforcement layer and sandwiched between metal plates to achieve uniform distribution and enhanced material properties.	High
	Spontaneous Infiltration	Turbine nozzle, Combustion liner.	A nano-composite, often comprised of woven fibers or ceramics, undergoes a perform pattern and is impregnated in a molten matrix, facilitating spontaneous infiltration and enhancing material properties.	High
Solid	Powder Metallurgy	Appropriate for intricate components and applications demanding elevated strength.	The synthesis involves controlling the powder size, ensuring compactness, and applying specific pressure, temperature, and duration during the sintering process to achieve desired composite characteristics.	Moderate
	Diffusion Bonding	Suitable for the fuselage and various structural components.	Precise control of temperature, duration, and bearing pressure is essential for fostering metallurgical bonding and optimizing the composite material properties.	High
	Friction Stir Process	Large volume fuel tank, nose barrier beam, Engine Part.	Non-consumable rotating tool stirring and heating a metal workpiece, followed by controlled deformation to achieve refined microstructures and improved material properties.	High

A noteworthy solid-state manufacturing method, such as spark plasma sintering (SPS) utilizing low voltage and direct current, stands out. SPS allows for the production of high-density composites characterized by excellent grain development and superior mechanical properties. Although it is a relatively expensive process primarily suited for basic symmetrical designs, SPS is a swift method that contributes to the production of advanced composites [20, 30, 31]. Hot isostatic pressing (HIP) employs casting and powder metallurgy processes for composite formation. The effectiveness of HIP processing is influenced by material structure, porosity, and density. One drawback of this method is the need for additional processes for all produced components. Nevertheless, HIP is considered a superior method for enhancing composite performance in structural applications. Ultrasonic-assisted casting (UAC) is another technique that aids in composite formation. UAC promotes the development of composites with favorable mechanical and homogeneous qualities, facilitating mass production [30, 31]. Friction Stir Processing (FSP) emerges as an effective technique that overcomes challenges associated with melting-related processes. It is adept at creating both surface and bulk composites with temperatures below the matrix's melting point, ensuring environmental friendliness. FSP eliminates porosity, encourages an even distribution of reinforcement particles, and results in fine-grained composites. Despite its somewhat higher cost due to necessary tooling, FSP utilizes localized, severe plastic deformation to alter the material's characteristics. Literature highlights significant improvements in performance behavior, hardness, and wear rate with the application of FSP [32, 33].

4. APPLICATIONS

The utilization of Al-based metal matrix composites holds immense potential owing to their exceptional characteristics and a high degree of customization they offer. It has been observed that employing nano-sized particulates as reinforcement and hybridizing reinforcement can significantly enhance and tailor the properties of Al-based composites in comparison to both Al-based alloys and composites reinforced with micron-sized particles alone. Through the judicious selection of constituents in Al-based hybrid and nano composites, various functionalities can be intentionally designed and achieved.

4.1 Structural Applications

The primary challenges in structural applications revolve around achieving optimal strength and stiffness. Al-based composites present a competitive level of specific strength and stiffness. Apart from their exceptional specific stiffness and strength, applications in structural contexts necessitate elevated bearing strength, resilience to harsh environments, resistance against outgassing, efficient through-thickness thermal conductivity, notable wear resistance, strong dimensional stability, effective resistance to impacts and erosion, resilience against burning, and adaptability for use in high-temperature scenarios. Al-based composites exhibit enhanced performance across these criteria. The application of Al-based composites in fracture-critical scenarios, exemplified by their use in the tire stud and drive shaft of the Chevrolet S-10, provides substantial evidence of their efficacy. Further enhancements in properties can be attained through achieving a more uniform distribution and finer particulate sizes. [34].

4.2. Thermal Applications

Properties such as elevated heat conductivity, specific heat conduction, and thermal expansion of coefficient are crucial heat-related uses such as bases for computer processor chips, power semiconductor devices in telecommunications, constituent parts in aerospace systems, and automotive purposes. Al-based composites prove to be valuable for these applications, as evidenced by the use of Al/SiC composites in satellite microwave systems, flip chip lids in networking and telecommunications, as well as intake and exhaust valves in the Toyota Altezza [34]. Reports indicate the advancement of hybrid composites based on aluminum for applications involving elevated temperatures incorporating reinforcements such as SiC, Al_2O_3, and TiB_2 [35]. The incorporation of nano-sized SiC reinforcement in aluminum exhibits superior dimensional stability, making it suitable for thermal applications that demand high dimensional stability [36].

4.3. Precision Applications

In numerous precision applications, the demand for outstanding resistance to distortion arising from thermal and mechanical loads is crucial. This requirement is particularly evident in devices like hard disk drives, video recording heads, atomic force microscope support frames, robotic arms, satellite antennae, and high-speed manufacturing equipment. Al-based composites offer enhanced resistance to these conditions, exemplified by their application in critical components such as the space shuttle mid-fuselage main frame and the Hubble Space Telescope antenna [34].

4.4. Wear Resistance

Wear resistance is a critical requirement for Al-based composites in various applications, including the piston and cylinder bore in engines, particularly in automotive brake systems (discs, rotors, pads, and calipers). Al-based composites present advantages such as high thermal conductivity, excellent wear resistance, reduced braking noise, low density for fuel economy, improved acceleration, and shorter braking distances. For instance, Al/SiC composites are utilized in the rear brake drums of the Volkswagen Lupo 3L and the Audi A2, while Al/SiC brake disks are employed in the Intercity Express (ICE) high-speed train in Germany [34]. Nano composites containing SiC, SiO_2, TiO_2, BN_3, and diamond embedded within matrix materials like Al, Ni, and Fe find applications in the automotive industry, significantly impacting the durability of car bodies and components [37].

5. ISSUES AND CHALLENGES

Both nano and hybrid composites demonstrate improved properties in comparison to monolithic materials and composites reinforced with single micro-sized particles. Despite the new opportunities created by these advancements, addressing various challenges is essential to make them practical for engineering applications and commercially viable on a broad scale. Key concerns and obstacles in nano and hybrid composites include:

(a) Implementing fabrication/processing techniques to achieve a consistent distribution of reinforcement in the matrix and ensure effective interfacial bonding.

(b) Addressing formability concerns arising from reduced ductility.

(c) Enhancing mechanical properties concerning volume fraction and particle size, understanding strengthening mechanisms, and comprehending the role of individual reinforcements in hybrid composites.

(d) Evaluating tribological properties, including wear and friction.

(e) Assessing the use of composites in corrosive environments.

(f) Considering factors related to thermal conductivity, thermal expansion, and dimensional stability at high temperatures [36].

The performance of Al-based metal matrix composites heavily relies on volume fraction and particle size. There is a necessity to refine existing processing methods for the fabrication of Al-based nano and hybrid composites and explore new techniques. Formability emerges as a critical issue since the addition of reinforcement particles reduces the ductility of composites, making them unsuitable for forming. It is crucial to develop composites without compromising ductility. The weight loss of composites is significantly influenced by volume fraction and particle size [40-43]. To achieve enhanced mechanical, tribological, and other properties for Al-based composites, the focus should be on processing techniques, process parameters, process control, and handling of large volume fractions, particle size, and interface, methods to enhance wettability and uniform distribution, and performance under extreme service conditions [37, 45].

Developing composites without compromising toughness, producing low-cost reinforcement particles, and refining secondary processing techniques for large-volume production with low cost, recyclability, and commercial viability are essential aspects requiring attention [46,38]. Special attention must be given to addressing environmental and cost issues related to aluminum matrix nano and hybrid composites to expand their use as alternative lightweight materials. Environmental conditions significantly impact the performance of Al matrix composites, and the corrosion behavior of aluminum matrix composites in various environments is a crucial selection criterion for specific applications. Various forms of corrosion associated with Al matrix composites include pitting corrosion, galvanic corrosion, crevice corrosion, stress corrosion cracking, corrosion fatigue, and tribo-corrosion. The primary sources of corrosion for Al matrix composites include galvanic corrosion between the matrix and reinforcement, chemical degradation of interfaces and reinforcements, corrosion due to processing conditions of Al matrix composites, and resulting microstructures. Corrosion-resistant AMCs can be produced by controlling the microstructures of composites, processing conditions, and interactions at the composite interface [39].

The cost of fabricating AMCs with nano-sized reinforcement is generally high due to the elevated cost of obtaining nano-sized reinforcement. Despite the development of various synthesis and production techniques for nano reinforcement (particles and fibers), there is a need to create methods that can produce nano-sized reinforcement in large quantities at an affordable cost. Processing techniques for nano and hybrid AMCs that ensure a uniform distribution of reinforcements, preserve the nanostructure in the end product without excessive grain growth, and allow bulk production to reduce costs are essential[48]. The control and optimization of process parameters play a pivotal role in reducing the production costs of nano and hybrid AMCs.

6. CONCLUSION

The evolution of Aluminum-Based Metal Matrix Composites (MMCs) presents a promising trajectory, marked by advancements in fabrication techniques and applications. These composites, designed to combine the advantages of metals with the enhanced characteristics provided by reinforcements, exhibit exceptional properties in terms of strength in mechanics, thermal conductivity, and resistance to wear. The demand for high-performance materials in aerospace, automotive, and other industries has propelled research in Aluminum MMCs, replacing traditional alloys in critical components. The literature review underscores the versatility of fabrication methods, emphasizing powder metallurgy and stir casting as prevalent techniques. Hybrid Aluminum matrix composites, incorporating diverse reinforcements, showcase stability and uniformity in microstructure, contributing to superior mechanical properties. From nano-sized SiC reinforcement to utilizing waste materials for hybrid composites, researchers continue to explore innovative approaches, showcasing the adaptability and potential of Aluminum-based materials. Applications in structural, thermal, precision, and wear-resistant domains demonstrate the diverse capabilities of Aluminum MMCs. Their efficacy is evident in critical components like the space shuttle mid-fuselage main frame and Hubble Space Telescope antenna, affirming their resilience in fracture-critical applications. Furthermore, their use in thermal applications, precision instruments, and automotive components highlights the broad spectrum of their applicability. However, challenges persist, ranging from uniform reinforcement distribution to formability concerns and environmental considerations. Addressing these issues requires a concerted effort in refining fabrication processes, optimizing parameters, and developing cost-effective methods for producing nano-sized reinforcements. Additionally, environmental and cost concerns necessitate further exploration to establish Aluminum MMCs as viable alternatives in various industries. In conclusion, the ongoing research in Aluminum-based composites presents a dynamic landscape with opportunities for continued innovation, ensuring these materials contribute significantly to the evolution of high-performance engineering applications.

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