A Comprehensive Review of Metal Matrix Composites: Materials, Methods, and Performance

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Abstract. Metal Matrix Composites (MMCs) have emerged as an important class of engineered materials in which the ductility and toughness of metallic matrices are combined with the strength and functional capability of ceramic or carbon reinforcements. The review summarizes recent developments, identifies gaps, and assesses the prospects of MMCs for applications in the automotive, aerospace, and biomedical sectors. It covers traditional methods of processing, such as stir casting and powder metallurgy, and new techniques, including ultrasound-assisted casting and additive manufacturing. Particular attention has been paid to interfacial engineering, nano and hybrid reinforcement designs that promote microstructural uniformity and load transfer efficiency. Current practices are highlighted with their advantages and disadvantages, along with challenges in nanoscale dispersion and future research directions in processing and environmentally sustainable strategies.

Keywords: MMCs, Aluminum alloys, Reinforcements, Mechanical properties, Aerospace and automotive applications

1 Introduction

During the last few decades, Metal Matrix Composites have attracted much attention as advanced materials due to the deficiencies of conventional monolithic metals and alloys. They combine the ductility and toughness of metals with the hardness, wear resistance, and thermal stability of ceramics or nanomaterials. Such a unique combination of properties is achieved by reinforcing metallic matrices that include, but are not limited to, aluminum, magnesium, copper, titanium, and nickel with secondary phases in various forms such as particulates, whiskers, or fibers, including carbon nanotubes (CNT) and graphene. These lead to materials with tailored properties for improved strength-to-weight ratios, better tribological performance, and comparable or superior thermal and electrical conductivities than those of conventional alloys[1].
These three aspects materials, processing, and applications are interrelated and form the basis for the development of MMCs. The microstructure and nature of the reinforcements determine the stability of the reinforcement and its bonding with the matrix. The processing methods liquid processing, stir and squeeze casting, solid-state processing, powder metallurgy, and hot pressing, and new processing methods like additive manufacturing and friction stir processing control properties like porosity,

J. Saxena et al. (eds.), *Proceedings of the International Conference on Sustainable Micro-Nano Materials & Innovative Technology (ICSUMMIT 2026)*, Atlantis Highlights in Engineering 44,
https://doi.org/10.2991/978-94-6239-727-9_4

wettability, and distribution of reinforcement. Reproducibility, scalability, and economic viability ensure industrial acceptance of MMCs[2].
Applications of MMCs include aerospace, where the requirement is for lightweight and strong components; in automotive for reinforced brake rotors and drive shafts, which require high wear resistance and thermal stability; in electronics for heat sinks; and recently in biomedical areas with biocompatible MMCs reinforced with nanosilver and bio-ceramics. However, reinforcement clustering, inadequate interfacial bonding, uniform dispersion of nanoscale reinforcements, and high production costs are some challenges that limit this material family to transition from the laboratory scale research to mass production. The current state of progress, therefore, with the driving forces of computational materials science, nanotechnology, and hybrid composite design, tries to address this gap between material fabrication and applied usage[3].

2 Material Selection and Classification of Metal Matrix Composites

Metal Matrix Composites are a group of advanced composite materials made of a metallic matrix strengthened with secondary phases like ceramic particles, fibers, or whiskers to increase the overall properties of the material. The matrix material used in MMCs is most often a metal or metal alloy that provides ductility, toughness, and thermal or electrical conductivity [4]. Reinforcements added to the matrix enhance mechanical strength, stiffness, wear resistance, and thermal stability. Light metal, despite having favorable strength-to-weight-ratios and high resistance against corrosion, is frequently selected as the matrix material [5]. For example, the use of ceramic phases (SiC, Al_2O_3, B_4C) or carbon or graphite fiber to reinforce composite is often used in order for the composite to have high strength and hardness [6].Their classification can be understood on the basis of matrix material, reinforcement type and number of reinforcements.

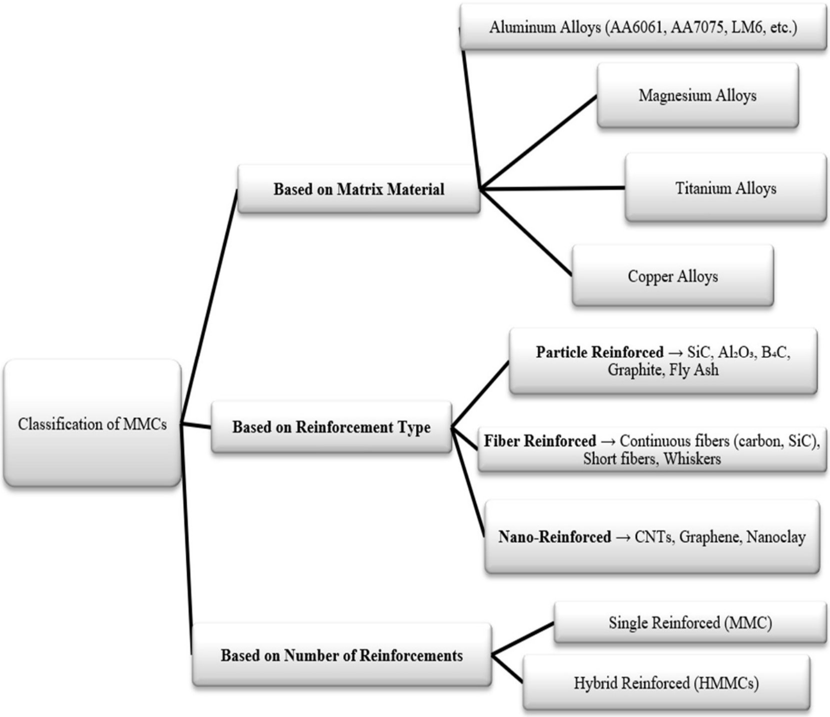

Fig. 1. Classification of Metal Matrix Composites

2.1 Based on Matrix Material:

The choice of matrix material has a strong influence on mass, mechanical properties, and high-temperature stability in MMCs. Aluminum Alloys (AA6061, AA7075, LM6, etc.) are used most widely in matrix systems, as they have low density, good corrosion resistance, and easy machinability. For example, Al6061 composites containing B_4C and graphite were produced by Yunus et al. for automotive applications with improved wear resistance and strength[7].

2.2 Based on Reinforcement Type:

Reinforcement fillers are added to enhance hardness, stiffness, and wear or functional properties.

2.2.1 Particle Reinforced MMCs:

With the addition of SiC, Al_2O_3, B_4C, graphite, or fly ash, wear resistance, hardness, and mechanical stability could be increased. Investigated the tribological performance of particle-reinforced Al-MMCs and noted that SiC- and B_4C-incorporated MMCs showed enhanced wear.

2.2.2 Fiber Reinforced MMCs:

These have continuous or short fibers to offer high strength and stiffness for load-bearing applications.

2.2.3 Nano Reinforced MMCs:

The addition of CNTs, graphene, and nano-clays results in extraordinary improvement in the hardness, tensile strength, and tribological behavior as a result of high surface-to-volume ratios.

2.3 Based on Number of Reinforcements:

Single reinforced MMCs are reinforced by a single reinforcement, e.g., SiC or Al_2O_3. Although successful, these methods may be lacking in terms of balanced multifunctionality. Hybrid Reinforced MMCs are further combinations of two or more reinforcements with the aim to get both mechanical and tribological properties. Chelladurai et al. also described HMMCs' promise of simultaneous high wear resistance and mechanical strength[8].

3 Fabrication Methods

The processing route of MMCs significantly controls the microstructure and reinforcement distribution, as well as overall tribological and mechanical behavior. Selection of the fabrication method not only controls the bonding between matrix and reinforcement but also determines the potential application of a composite in industrial fields such as aerospace, automotive, and defense.

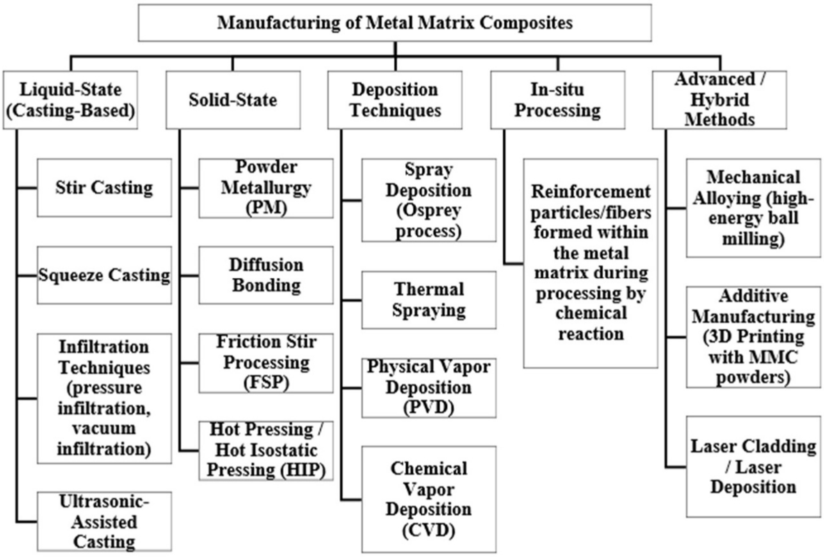

Fig. 2. Classification of Metal Matrix Composites

3.1 Liquid-State

Liquid metallurgy processes like stir casting, squeeze casting, and ultrasonic-assisted casting are most frequently utilized due to ease, affordability, and scalability. For instance, P et al. efficiently produced Al6061–B_4C–graphite composites by stir casting and showed improved hardness and wear resistance for automotive use[9].

3.1.1 Stir Casting: It is stirred with reinforcement particles into melted metal prior to casting. It is a cost-effective approach for the mass production of aluminum MMCs but suffers from problems such as porosity and particle clustering [10].

3.1.2 Squeeze Casting: Squeeze casting is an advanced metal processing technique that has received considerable interest in the recent period due to the combined advantages of casting and forging. In this process, molten metal is introduced into a preheated die and solidified with high applied pressure, yielding components with improved mechanical properties, less porosity, and a good surface finish [11].

3.1.3 Ultrasonic-Assisted Casting: Ultrasonic vibrations on molten alloy result in uniform reinforcement dispersion, especially nano-additives such as CNTs and graphene. Bhoi et al. have highlighted its effectiveness for mitigating the problem of agglomeration [12].

3.1.4 Infiltration Techniques (Pressure/Vacuum): Among the different techniques, infiltration techniques such as pressure and vacuum infiltration are widely used in the processing of MMCs, as they allow achieving near-net-shape composites with a high-volume fraction of reinforcement. Another report by Clyne and Withers illustrated the capability of vacuum infiltration to make Al-Al_2O_3 composites with a homogeneous distribution of particles that reduced casting defects [13].

3.2 Solid-State Methods

In contrast, solid-state techniques in the form of powder metallurgy, friction stir processing, and ball milling allow better reinforcement distribution and interfacial adhesion. Gafur et al. highlighted that the powder metallurgy path brings homogeneity to the microstructure, even for nano-reinforced MMCs; however, they are expensive and not adapted to mass production[14]. Processing techniques, therefore, continue to be an important classification parameter that directly influences the structural and functional properties of MMCs.

3.2.1 Powder Metallurgy: PM is a highly versatile and most common method for producing MMCs with high advantages over liquid-state techniques because it can attain homogenous dispersion of the reinforcement and even create near-net-shape parts.

3.2.2 Diffusion Bonding & Hot Isostatic Pressing (HIP): Diffusion bonding is a joining process wherein intimate contact of clean surfaces under high temperature and under moderate pressure enables atoms to diffuse across the interface without melting. This technique allows fabricating multilayered or composite structures with minimal distortion and controlled reinforcement-matrix interfaces [15]. In contrast, HIP includes exposing powders or preforms to simultaneous high pressure and high temperature in an inert gas, usually argon. Such a technique eliminates residual porosity and enhances densification and homogeneity in the distribution of reinforcement within the matrix [16].

3.2.3 Friction Stir Processing: A technique in the solid state, wherein a rotating tool stirs reinforcements into the matrix. It does improve grain refinement and bonding while avoiding defects in casting. Friction stir processing has emerged as an efficient solid-state process to refine microstructures and enhance the distribution of reinforcements in MMCs. Several research works have documented that FSP facilitates homogeneous dispersions of ceramic and carbon-based particles while concurrently removing casting defects [17].

3.3 Deposition Techniques

Deposition is considered one of the major techniques within materials engineering, which allows thin films and coatings to be deposited with controlled composition, thickness, and microstructure.

3.3.1 Spray Deposition: Provides quick solidification with a fine microstructure and is suitable for bulk billets. Spray deposition, and the Osprey process in particular, is a near-net-shape manufacturing route wherein molten metal, atomized by an inert gas stream into fine droplets, is directed onto a substrate where they consolidate into a dense preform. Li et al. applied the Osprey method to manufacture mill rolls, with superior wear resistance and service life compared to conventionally cast rolls [18].

3.3.2 Thermal Spraying: Thermal spraying is a family of processes in which feedstock material is melted or softened and propelled at high velocity toward a substrate to create coatings. surveyed thermal spray coatings in the steel industry, where there is an improvement of corrosion and wear resistance upon exposure to a harsh environment, while underlining the importance of interfacial bonding and porosity control for durable ceramic coatings [19].

3.3.3 PVD and CVD: These produce thin-film coatings with very effective adhesion and high hardness. CVD allows modification of surface chemistry and integrates ceramic reinforcements at the nanoscale, while PVD techniques provide thick and uniform coatings that contribute to corrosion resistance, hardness, and thermal durability [20].

3.4 In-situ Processing

The in-situ methods involve the formation of reinforcement particles within the matrix through chemical reactions during fabrication.

Fig. 3. In-situ Process

3.5 Advanced / Hybrid Methods

3.5.1 Mechanical Alloying: Produces MMC powders with fine reinforcement distribution at the nano-scale. Often followed by sintering or HIP. In studies dealing with Al-based MMCs reinforced with SiC, B_4C, and carbon nanotubes, it has been demonstrated that mechanical alloying results in very homogeneous powders and clean reinforcement matrix interfaces, which are beneficial for achieving better load transfer efficiency [21].

3.5.2 Additive Manufacturing: This is 3D printing with metal matrix composite powders. It allows complex geometries and functionally graded MMCs. Though still expensive, it represents the future of MMC production [22].

4 Characterization of MMCs

Characterization of Metal Matrix Composites involves evaluating their properties to ensure they meet the desired performance criteria. This will normally involve the analysis of “microstructure” to ascertain the distribution of the reinforcement particles, determination of the “mechanical properties” that may include hardness, tension strength, and flexural strength, and “tribological tests” to establish wear resistance.

4.1 Microstructural Characteristics

The descriptive word microstructure is applied in order to define the inner structure and material composition. Moreover, the microstructure of a material provides information on the microscopic structure of material constituents. The constituents of microstructure are isolated from each other through grain and phase boundaries. This structural composition affects material properties regarding mechanics, heat properties, and electricity.

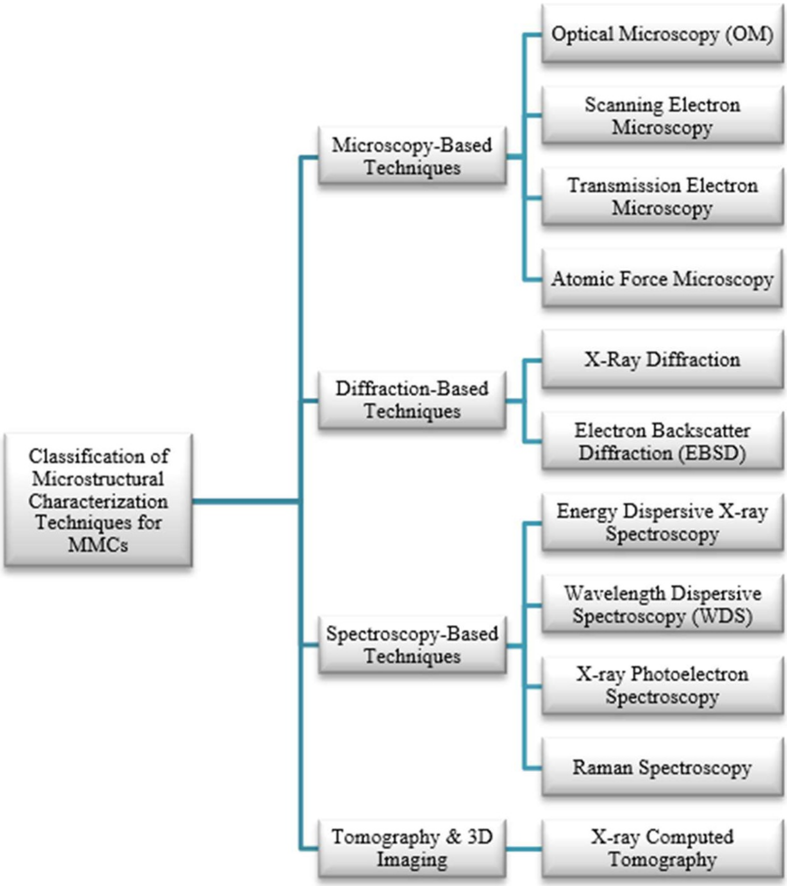

Fig. 4. Classification of Microstructural Characterization Techniques for MMCs

Furthermore, the study of advanced approaches towards the characterization of MMNCs becomes necessary to gain in-depth knowledge about the microstructural properties of MMNCs. Scanning Electron Microscopy and X-ray Diffraction analysis help in gaining in-depth knowledge about the distribution of nanoparticles in the matrix, thereby understanding the relationship between microstructural properties and the mechanical properties of MMNCs. [23].

4.2 Mechanical Characteristics

Besides the economics of going green, updateable MMNCs are also now a challenge as well as an opportunity for the manufacturers. With the increasing demand for these advanced materials, efficient and quality ways of production are required [24]. For instance, digital twin technology used in a manufacturing line would thus allow the monitoring and optimization of MMNCs in-situ to keep their characteristics at optimal levels while reducing waste amounts[25].

4.3 Tribological Characteristics

The increasing demand for better performance of materials by different industries has brought MMNCs to the frontline in material innovation. These composites combine, through unique ways, the advantageous properties of diverse reinforcements like silicon carbide and Al2O3, hence deriving remarkably improved mechanical strength and wear resistance [26].

5 Application of MMCs

MMCs have been established as sophisticated materials and structural components with a unique ability to provide high strength, stiffness, hardness, corrosion resistance, and thermal stability simultaneously. They have applications in various sectors: aero-space, auto-sports, defense, marine, sport, and biomed applications.

Aerospace Applications:

Aerospace engineering is the major consumer of MMCs due to their high strength-to-weight ratio, fatigue life, and thermal stability[27]. Aluminum-silicon carbide and aluminum-graphite composites have major applications in the fuselage, wings, and landing gear of aircraft due to the need for high strength and light weight [28]. In the case of spacecraft and satellites, the primary application of MMCs is to provide dimensional stability and resist thermal expansion, which is highly necessary in extreme environments [29]. Titanium and nickel metal matrix composites reinforced with ceramic fibers have major applications in jet engines and turbines due to creep, fatigue, and oxidation at high-temperature exposures [30].

Automotive Applications:

In the auto part field, MMCs find their use in the reduction of weight as well as the increase in the performance of the vehicle. For instance, the use of Al-SiC and Al_2O_3 as reinforcement in the composition gives better wear resistance than the traditional material, which is iron cast [31]. In the engine part, the use of pistons, cylinder liners, and connecting rods consisting of MMCs provides better friction, higher thermal conduction, and durability [32]. In addition, the increased torsion strength and fatigue life, brought about by the use of MMC drive shafts and propellers in high-performance cars, directly increases their mileage life.

Marine Applications:

The marine industry is challenged by factors such as corrosion, wear, and heavy loading, for which MMCs offer a good alternative compared to traditional alloys. Aluminum based MMCs find applications in high-speed boats and ships for light weight and fuel efficiency reasons [33].

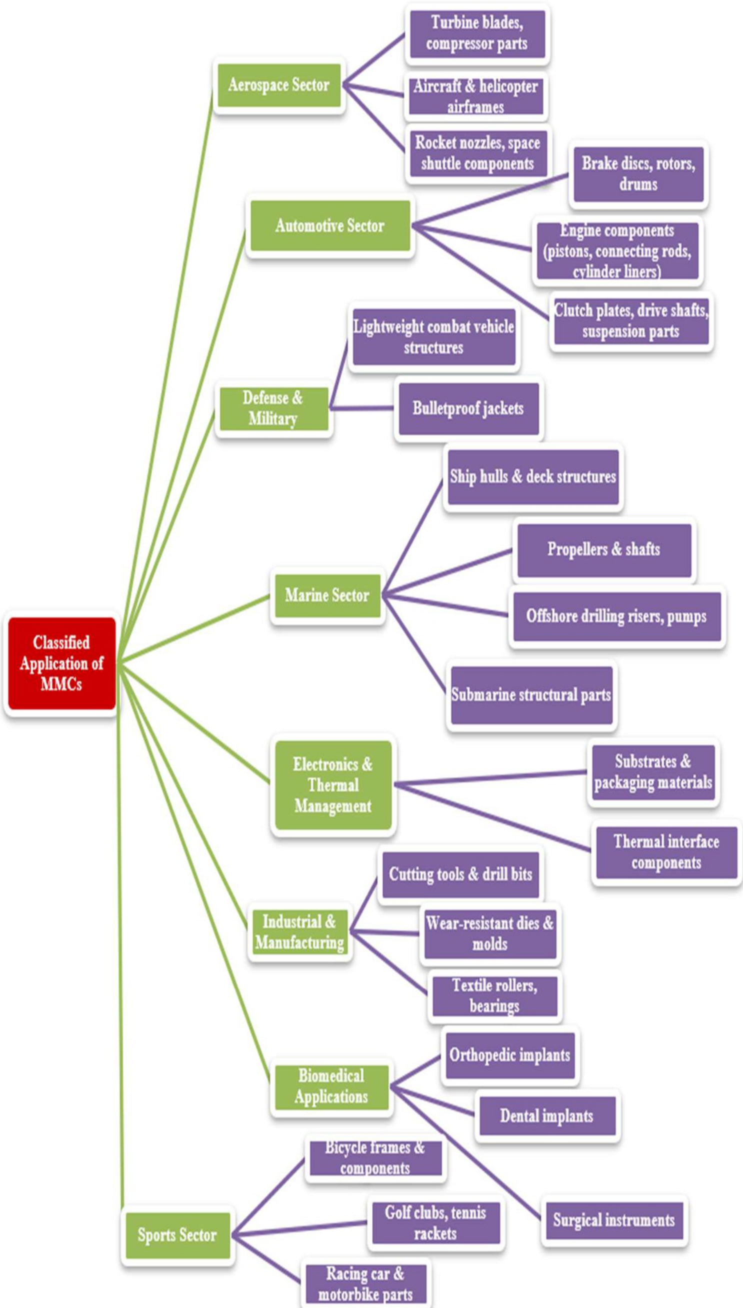

Fig. 5. Classified Application of MMCs

Biomedical Applications:
Biomedical engineering has seen the application of MMCs, with titanium based MMC being widely used because it is biocompatible, wear-resistant, and has load-bearing capacity. Biomedical engineering applications of titanium-based MMC include bone plates, hip joint components, and implants, apart from requiring strength, it must be biologically accepted [34]. Silver-based MMCs, along with graphene, are biologically active; therefore, it is useful for dental fillers, surgical instruments, and bio-medicated coats [35].

Electrical and Electronic Applications:
MMCs have widespread applications in electrical and electronic industries due to their high thermal conductivity, low coefficient of thermal expansion, and good dimensional stability. Aluminum-SiC and copper-carbon composites have been used extensively in heat sinks, power electronic, laser, and LED device substrates, where efficient heat dissipation is an important factor for device survivability [36]. Additionally, MMCs have been applied in semiconductor device packaging, where thermal expansion differences could have caused device failure [37]. Carbon fiber reinforced MMCs have been applied in electrical contacts and conductive interconnections for advanced circuits, for applications involving repeated heating and cooling.

Energy Sector Applications:
The energy, both conventional and renewable, sectors have employed the use of MMCs for high-performance applications. In wind turbines, the use of MMC materials in shaft, bearing, and gear components is for improved fatigue strength and a decrease in maintenance requirements [38]. In the nuclear fields, zirconium-based MMC materials are undergoing research for use in the cladding of fuel rods because of their neutron transparency, corrosion resistance, and strength against high temperature. Also, materials reinforced with carbon, graphite, or graphene are being researched for the manufacture of electrodes for lithium-ion batteries and hydrogen fuel cells, primarily for improved conductivity, strength, and efficiency of energy usage [39].

Industrial and Tooling Applications:
Machining, manufacturing, and heavy machinery are some sectors where MMCs are in high demand because of their high wear resistance and thermal stability. Aluminum alloys with titanium as matrix material combined with ceramics viz., SiC, Al_2O_3, and B_4C are used as cutting tools, machining tool inserts, dies, which improve tool life even in high temperature and high load conditions [40]. In the casting industry as well as in injection molding, MMCs are used as dies & mold materials. Since wear rate of die material as well as life of dies are less as compared to conventional steels. In addition to this, in rollers, bearings, tribological components, and in heavy industries, MMCs are used as self-lubricating materials with high wear resistance.

MMCs have been shown to be very versatile materials, whose applications range across several fields, such as the aerospace, automotive, defense, marine, biomedical, sports, electronics, energy, and construction sectors. The rare combination of being very lightweight, strong, having a good wear and corrosion resistant property, coupled with a good high-temperature stability, makes them superior to conventional alloys, both structurally as well as functionally. Even though the aerospace, automotive sectors dominate the usage of MMCs, the applications of these materials in the biomedical, electronics, and renewable energy sectors have come forth and emphasized the increasing importance of these materials in the realm of engineering today [41]. Even though the cost of manufacture of these materials is a concern, the very fact that they possess a vast number of successful applications establishes the fact that these materials not only possess the potential of being superior materials over the traditional contenders, but they also have the potential for being the materials for the next generation products [42].

6 Future Scope

Future studies on MMCs are projected not only to focus on the conventional ones but would rely extensively on the emerging areas in trying to meet the demands of performance and sustainability. These would involve the use of nanofillers such as graphene, CNTs, or nano-clays incorporated in trying to attain high strength indexes with multifunctionality, leading mainly to aerospace or electronic components. Improved distribution of the reinforced materials would be made possible with the use of processes such as additive manufacturing. The uses of MMCs would increase in the areas of renewable energy, biomedical devices, or high-end electronic devices focusing on sustainability with satisfactory performance.

7 Conclusion

MMCs are being explored and utilized increasingly in the form of multifunctional materials in the field of engineering applications. Aluminum based MMCs, which are increasingly using aluminum alloys such as AA6061, AA7075, and LM6, have attracted significant attention due to the synergy of the beneficial properties of low density, specific strength, and processing advantages. Hybrid reinforced materials, which intend to enhance the efficacy of the mechanics, stability, and electrical conductivity of the materials by combining ceramic materials such as SiC, B_4C, and Al_2O_3 with nanomaterial, appear to be the trend in the development of MMCs. There are substantial challenges in the industry waiting to be addressed by MMCs related to sustainability, costs, and scale ability in future engineering applications.

Disclosure of Interest. Two authors were members of the conference organizing committee and were not involved in the review or decision process for this manuscript.

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