RECENT ADVANCEMENT IN METAL MATRIX COMPOSITES: MATERIAL, METHODS AND APPLICATIONS

**Abstract**

The development of metal matrix composites (MMCs) has seen significant advancements in fundamental science and technology. These advancements include gaining a deeper understanding of composite behavior, the role of fiber-matrix interfaces, surface coatings, various manufacturing processes, and thermal-mechanical processing techniques for MMCs. This knowledge has not only led to the improvement of MMC technology but also paved the way for the development of high-temperature intermetallic-matrix composites.

The pursuit of lightweight materials with improved properties for various applications has given rise to a new class of materials known as Metal Matrix Composites (MMCs). These composite materials offer excellent physical, mechanical, and developmental properties, making them widely applicable in industries such as aircraft technology, automotive, defense, electronics, and space applications. The versatility of MMCs has led to extensive research and development in the field of production technologies, resulting in cost reductions and increased acceptance in the market.

The objective of this paper is to provide a comprehensive summary of the present application status of MMCs and the various fabrication methods currently employed in their production. By reviewing the current state of MMC technology and fabrication techniques, the Chapter aims to shed light on the promising potential of MMCs as advanced materials in various industries.

**Key word: Metal matrix composite, Application, AMC**

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# INTRODUCTION

Industrial revolution has been made since long back and during this revolution various manufacturing machines, methods have been invented to cater the nations requirements. The functionality of our manufacturing system, daily necessities, communication, and transportation all rely on the properties and applications of materials. Over the recent decades, composite materials have gained significant popularity due to their superior properties and versatile applications. Composites are advanced materials in which reinforcement is distributed within the matrix, either in a continuous or discontinuous phase. In the 1950s, the concept of metal matrix composites emerged, incorporating two distinct phases: the matrix phase and the reinforce/dispersive phase. Challenges associated with the implementation of these composites include expensive fabrication methods and specific issues in certain applications, like foreign object damage and erosion in engine fan components[1]. In the past decade, the significance of MMC (Metal Matrix Composite) materials has grown significantly, driven by their notable benefits, including a high strength-to-weight ratio, excellent wear and corrosion resistance. These materials are now being utilized in diverse industries, such as automotive, aerospace, and other sectors involved in spare parts manufacturing[2]. The mechanical properties and tribological performance of aluminium metal matrix composites, containing various types of reinforcements, surpass those of traditional engineering materials used in the past. These composites exhibit lower weight, enhanced cost-effectiveness, improved strength, superior stiffness, and reduced wear rate[3].

Over the past two decades, particulate reinforced aluminium matrix composites (PRAMCs) have emerged as promising candidates to supplant traditional materials across various application domains, including transportation, military, marine, and advanced engineering industries. The addition of reinforcing particles in the aluminium matrix alloy significantly enhances the tribological and mechanical properties of AMCs (Aluminium Matrix Composites). Various widely employed fabrication methods for these composites include compo casting, infiltration, vacuum casting, powder metallurgy, stir casting, in-situ casting, and squeeze casting. Out of the available processes, stir casting stands out as the most promising method for manufacturing particulate reinforced aluminium matrix composites. This technique ensures a uniform dispersion of reinforcement particles within the matrix alloy[4] The stir casting method is favored for metal matrix composite production due to its ability to minimize damage to the reinforcement material. The most cost-effective approach for fabricating metal matrix composites is the liquidity state method among all available methods. This technique allows for the effective production of larger casting components. Additionally, increasing the weight percentage of reinforcements in the aluminium metal matrix enhances strength while reducing ductility[5] Aluminium metal matrix composites refer to composites where aluminium is strengthened through the addition of other metals, organic compounds, or ceramics. The reinforcement in aluminium matrix composites (AMCs) can take the form of particulates, continuous or discontinuous fibres, and whiskers, depending on the specific industrial application[6].

Aluminium matrix composites have a strong potential to serve as replacements for copper alloys. The ease of melting aluminium metal or aluminium alloy and using it as a matrix material makes it a more favourable choice compared to copper alloys. When dealing with copper matrix composites, researchers utilized die compaction as a preferred method due to the high melting point of copper, which exceeds the range of 1000°C. Additionally, the toxicity of certain copper alloys limits their processing options to powder metallurgy[7]. Hybrid composites exhibit superior mechanical properties when compared to metal composites with a single type of reinforcement. These hybrid metal matrix composites involve the incorporation of more than one type of reinforcement, varying in size, shape, and weight percentages, to achieve enhanced mechanical characteristics. The incorporation of hard ceramic particles such as SiC, Al2O3, MgO, WC, SiO2, and B4C into the aluminium matrix alloy is a common practice to enhance its mechanical properties. It has been observed that incorporating two different synthetic ceramic reinforcements into aluminium matrix materials can lead to enhanced mechanical behaviour, improved machining characteristics, and superior tribological properties in aluminium hybrid composites[8].

# SYNTHESIS OF COMPOSITES: (Various Methods of Manufacturing)

Manufacturing route adopted in fabricating any composite plays a vital role in determining the final properties of the composite. Numerous techniques are currently being utilized to produce high-quality MMC products. The fabrication methods for MMC products can be classified into three main categories

1. Solid-state processes.
2. Liquid-state processes.
3. Deposition processes.

**1 Solid-state processes.**

Powder metallurgy is a technique used to create metal matrix composites by blending fine powders of the matrix material (such as aluminium and its alloys) with reinforcing particles. The blending is done at room temperature or slightly above, and the resulting mixture is then compacted into the desired shape. Next, the compacted material undergoes solid-state sintering, which involves heating it in a controlled atmosphere below its recrystallization temperature. This process helps reduce porosity and remove any foreign matter introduced during compaction. After solid-state sintering, the composite undergoes deformation, extrusion, or forging above room temperature to further enhance its mechanical properties by reducing porosity and strengthening the bond between the matrix and reinforcing particles. Powder metallurgy allows for the production of precisely shaped components with complex attributes and high accuracy. It is crucial to ensure that all particles are uniformly and homogeneously distributed in the mixture when using this processing route. This even distribution of particles is essential to achieve a composite with a favorable microstructure and excellent mechanical properties. Proper mixing and distribution of the reinforcing particles within the matrix contribute significantly to the overall performance and quality of the final composite material[9].

The powder metallurgy processing technique is highly appealing as it operates at lower temperatures, offering better control of interface kinetics in theory. This method also enables the use of matrix alloy compositions and microstructural refinements that are achievable only through the utilization of rapidly solidified powders. Processing powder metallurgy composites involves specific and essential steps, as illustrated in Figure 1 Powder Metallurgy Processing.[10].

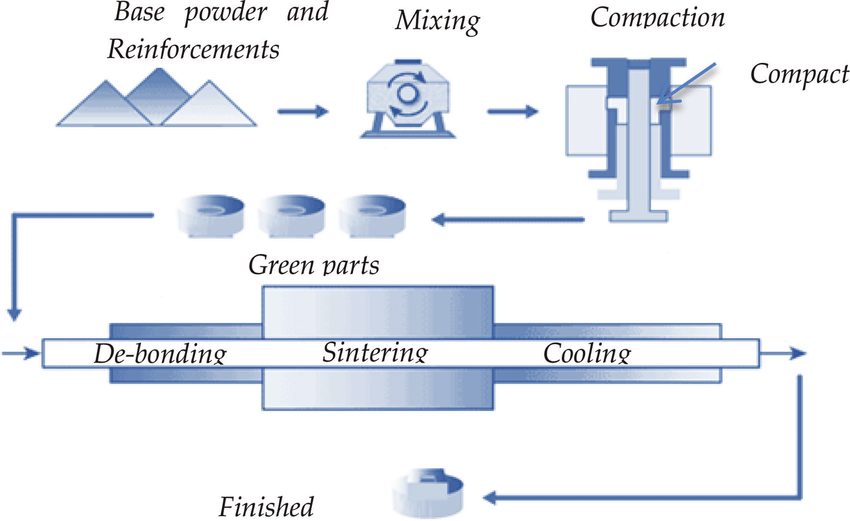


Figure 1 Powder Metallurgy Processing

1. **Liquid-state processes.**

Stir casting is a casting method that entails the mixing of a reinforcing agent into the base matrix material using a mechanically operated stirrer. This process is widely adopted in the development of MMCs due to its economic feasibility, capacity for mass production, ease of implementation, and its ability to improve the structural behavior of the composite. The stir casting process consists of a furnace, a mechanically operated stirrer, and a reinforcement dispenser. The base material is melted in the furnace through heating. In this process, a bottom pouring furnace is more suitable as it allows instant feeding of the molten mixture into molds, preventing the material from stabilizing at the bottom of the pot. Proper mixing of the molten matrix material and reinforcing material is crucial for achieving isotropic mechanical properties. This mixing is accomplished using a stirrer equipped with a stirrer rod and blades. The rotary motion of the stirrer generates swirls in the mixture, facilitating the thorough mixing of the molten materials. Mechanical stirrers can also be categorized based on their geometrical shape and the number of impeller blades they have. Among all types of stirrers, the most favorable one is the impeller with three flat blades. This design is preferred because it promotes the development of axial flow while also reducing power consumption during the stirring process. The speed of the stirrer can be controlled using a regulated speed motor connected to the stirrer, which provides the necessary rotary motion. To introduce the reinforcing material, a feeder is also positioned along with the furnace. Once the slurry is prepared, it can be poured into any type of Mold, such as sand Molds, permanent Molds, or investment Molds, based on the specific requirements of the casting process.

Figure 1 illustrates the series of different activities involved in the stir casting process. The procedure begins by placing the matrix material in a furnace equipped with a lower feeding mechanism. Prior to feeding, the reinforcing agent needs to be preheated to prevent moisture, contaminants, and other unwanted factors. For this preheating step, a separate furnace is used in parallel with the main furnace for the matrix material. This ensures that both the matrix material and the reinforcing agent are appropriately prepared before they are combined in the stir casting process. Once the desired temperature is reached, which is determined based on the matrix material being used, the mechanically operated stirrer is activated to generate a swirl within the molten matrix material. Along the axis of this swirling motion, the reinforcing agent is gradually introduced through the feeder at a steady rate. The process continues until the desired amount of reinforcing material is thoroughly mixed with the molten matrix material. This ensures proper dispersion and uniform distribution of the reinforcing agent throughout the mixture, resulting in a well-blended composite material[11].

Figure 2 Schematic diagram of Stir casting Method

1. **Deposition processes.**

The physical vapor deposition process is utilized for manufacturing metal matrix composites, and it is typically a slow procedure. In this method, a fiber is continuously passed through an area with a high partial pressure of the metal to be deposited. During this process, the metal vaporizes and then condenses onto the surface of the fiber, leading to the formation of the metal matrix composite as seen in Figure 3. In the physical vapor deposition process, a relatively thick coating is obtained on the fibre by passing it through a region where condensation occurs. To produce vapours, a high-power electron beam is directed onto the end of a solid bar feedstock. Typically, the deposition rates are around 5-10 μm per minute.

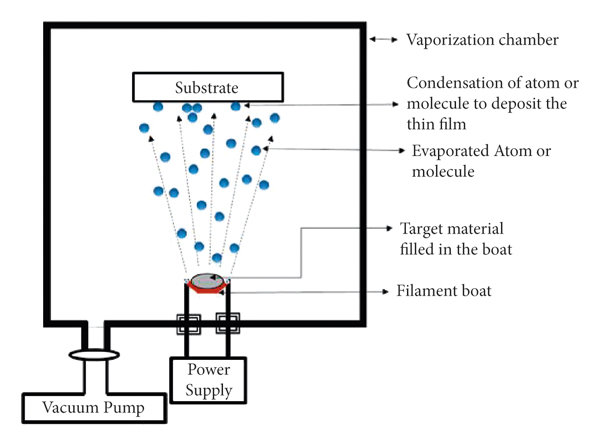


Figure 3 Schematic diagram of physical vapor deposition

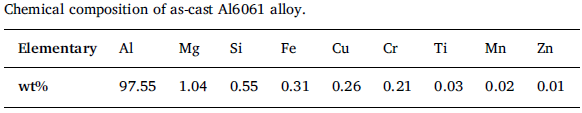
The coated fibres are then assembled into a bundle or array and consolidated using a hot press or hot isostatic pressing (HIP) operation to create the final composite material. This process ensures the proper bonding and integration of the coated fibers to form a strong and cohesive metal matrix composite. PVD (Physical Vapor Deposition) can be divided into two main categories:[9].

1. Vaporization and characterization techniques (EBED - Electron Beam Evaporation Deposition)
2. Sputtering techniques.

# Materials:

Numerous materials have been utilized to fabricate metal matrix composite. However, aluminium is one of the excellent material due to its higher strength to weight ratio, higher thermal conductivity and corrosion resistance as well as easy to cast in to intricate shape. The composition analysis of the Al-6061 alloy was conducted using atomic emission spectrometry, following the ASTM E1251-2011 test method. Atomic emission spectrometry is a technique used to determine the elemental composition of a material by measuring the wavelengths of light emitted when the sample is excited by a high-energy source, such as an electric discharge or a flame. The ASTM E1251-2011 standard provides guidelines and procedures for performing this analysis in a standardized and reliable manner[12].

Table 1 Spectroscopy of Al6061[13]



Following information depict the utilization of various aluminium material as matrix material to fabricate metal matrix composite and reinforcement used to enriched mechanical properties.

Table 2 Different Material for Fabrication of MMCs

| **Matrix material** | **Reinforcement** | **Processing Route** | **Reference** |
| --- | --- | --- | --- |
| ADC 12 | Boron carbide (B4C) | Stir Casting | [14] |
| Al6061 | Boron carbide (B4C), SiC | Bottom pouring stir casting | [15] |
| Al6061 | SiC-B4C | Stir Casting | [16] |
| Al6061 | SiC/WC | Stir Casting | [17] |
| Al6061 | Boron carbide (B4C) | Stir Casting | [18] |
| Al6061 | Boron carbide (B4C) | Stir Casting | [19] |
| LM24 | Boron carbide (B4C) | Stir Casting | [20] |
| Al6063 | Fly ash and Al2O3 | Stir Casting | [21] |
| Al−4.5%Cu | Bamboo leaf Ash (BLA) | Bottom pouring stir casting | [22] |
| AA6063 | SiC-TiC | Stir Casting | [23] |
| Al6061 | TiB2 | Stir Casting | [13] |
| AA7150 | WC | Stir Casting | [24] |
| Al6351 | Al2O3–C | Stir Casting | [25] |
| Al6061 | boron carbide and graphite | Bottom pouring stir casting | [26] |
| Al6061 | WC | Stir Casting | [27] |
| Al6061 | Al2O3 | Stir Casting | [28] |
| Al6063 | boron carbide | Stir Casting | [29] |
| Al7075 | WC and Fly Ash | Stir Casting | [30] |
| A356 | WC | Stir Casting | [31] |
| Al6061 | boron carbide and graphite | Bottom pouring stir casting | [32] |
| Al6061 | Boron carbide (B4C), SiC | Stir Casting | [33] |
| Al6061 | WC | Stir Casting | [34] |
| Al6061 | boron carbide | Stir Casting | [35] |
| AA7075 | Al2O3 | Stir Casting | [36] |
| AA6531 | Al2O3 and graphite | Stir Casting | [37] |
| Al7075 | WC | Stir Casting | [38] |
| Al7075 | WC and Cobalt | Stir Casting | [39] |
| Al5083 | Al2O3 and B4C | Stir Casting | [40] |
| Al6061 | B4C | Stir Casting | [41] |

Aluminium alloys are widely favoured as the matrix material in MMCs, both in research and industrial applications, primarily due to their outstanding strength-to-weight ratio. Additionally, aluminium alloys are cost-effective compared to other lightweight materials like magnesium and titanium. These alloys exhibit excellent mechanical properties, such as strength and ductility, and boast high corrosion resistance, making them versatile and adaptable to various requirements.

Among the various aluminium alloys, age-hardening grades (2xxx, 6xxx, and 7xxx series) are commonly used as matrix materials. Age-hardening alloys offer the advantage of further enhancing mechanical properties through different aging treatments, allowing for tailoring their characteristics to meet specific needs. This makes them a popular choice for developing high-performance metal matrix composites with superior mechanical capabilities[13].

# Application of Composites:

* **Automobile Components:**

Light alloy composite materials hold significant potential for various applications in the automotive engineering industry. They are commonly utilized in components such as pistons road, pistons, piston pin, covers, car disc brake, cylinder heads, crankshafts, main bearings, engine blocks, cylinder blocks. These composite materials, which combine lightweight alloys with reinforcing elements, offer advantages such as reduced weight, improved strength-to-weight ratio, and enhanced performance, making them ideal for enhancing the efficiency and performance of automotive components.

An excellent example of the successful application of aluminium composite materials in this context is the partially short fibre-reinforced aluminium alloy piston Figure 4. These pistons are engineered with a combination of aluminium and short reinforcing fibres, resulting in enhanced mechanical properties and performance compared to traditional pistons made solely from aluminium alloys. The incorporation of reinforcing fibres in the aluminium matrix improves the overall strength, durability, and resistance to wear and deformation, making them highly suitable for high-stress applications in internal combustion engines. This demonstrates the effectiveness of composite materials in optimizing automotive components and advancing the performance and efficiency of modern engines.[42]

Table 3 Some real-life application of Composites

|  |  |  |
| --- | --- | --- |
| **Manufacturer** | **Composite** | **Component** |
| Duralcan, Martin Marietta, Lanxide | Al/SiCp | Piston |
| Duralcan, Lanxide | Al/SiCp | Brake rotor, Calipers, liners |
| GKN, Duralcan | Al/SiCp | Propeller Shaft |
| Nissan | Al/SiCw | Connecting Rod |
| Dow Chemical | Mg/SiCp | Sprockets, pulleys, Covers |
| Toyota | Al/Al2O3 | Piston ring |
| Dupont, Chrysler | Al/Al2O3 | Connecting Rod |
| Hitachi | Cu/graphite | Current collectors |
| Martin Marietta | Al/TiCp | Piston, connecting rods |
| Honda | Al/Al2O3 | Engine blocks |
| Lotus Elisse, Volkswagon | Al/SiCp | Brake rotors |



1. (b)

Figure 4 short fibre reinforced composite Piston (a) , particulate reinforced composite Car brake disc (b)

Currently, the majority of metal matrix composites (MMCs) used in automotive applications are based on aluminium and its alloys. One of the primary reasons for using MMCs in automotive engines is to reduce the mass of reciprocating parts, resulting in lower noise and vibration levels. The use of aluminium and its alloys is widespread in the automotive industry due to their lightweight and cost-effective nature compared to other light metals like titanium and magnesium. In automotive engines, the piston crown is a common target for MMC implementation. The improved hot strength of MMCs allows for lighter pistons to be used, enhancing engine performance. Similarly, MMCs can be beneficial for piston pins and connecting rods. Among the excellent aluminium alloys, precipitation hard enable alloys like AI-Cu-Mg and A1-Zn-Mg-Cu are of particular interest for automotive applications.

Major automotive companies such as Toyota and Honda have commercially adopted Al-based MMCs in their engines. Toyota has utilized MMC pistons in its diesel engines, while Honda has employed steel wire reinforced aluminium connecting rods and Al–Si matrix MMCs (with 12% Al2O3) for cylinder blocks in their cars. This indicates the increasing importance of MMCs in the automotive industry for achieving lightweight, efficient, and high-performance engine components[43].

* **Aircraft Components:**

In aircraft manufacturing, a significant focus is on improving the thrust-to-weight ratio of engines. This can be achieved by either increasing thrust or reducing the weight of engine components. Such improvements place higher stress on materials and lead to elevated working temperatures, affecting various engine parts, particularly discs, blades, and shrouds.

Titanium-matrix composites with boron or silicon carbide reinforcement have demonstrated favourable properties at both room and elevated temperatures, making them suitable materials for fan blade applications in high-temperature environments. Monofilament reinforced composites, with matrices of titanium alloy or intermetallic like titanium aluminide, are currently leading in this field. Although titanium has a higher density compared to aluminum, it still exhibits excellent strength-to-weight and stiffness-to-weight ratios when compared to steels.

Continuous SiC fibre-reinforced Ti-MMCs are under development for aerospace applications in several countries, including the USA, UK, France, and China. These advanced materials show promising potential for enhancing engine performance and efficiency, contributing to the ongoing efforts to improve aircraft propulsion technology and achieve greater overall performance.

* **Defense Components:**

Metal matrix composites (MMCs) have found significant applications in various critical parts of missiles and other defense systems due to their unique properties and advantages. One notable application is in stiffness-critical parts of missiles, which were traditionally manufactured using beryllium. However, MMCs offer a viable alternative with a high-volume fraction (40%) of particle-reinforced aluminium, which is both cost-effective and avoids the toxicity concerns associated with beryllium.

Fins of guided weapons are another important application of MMCs due to their high stiffness. MMCs reduce the flexing of fins, thereby increasing the accuracy of the weapon. In armoured fighting vehicles like tanks, MMCs are used in components such as tracks and engine parts to enhance battlefield manoeuvrability. The use of MMCs leads to a reduction in overall weight, significantly improving the vehicle's manoeuvrability and survival rates.

Scramjet engines, employed in hypersonic missiles and aircraft, rely on high vehicle speed to compress incoming air forcefully before combustion. MMCs are chosen for the outside skin of hypersonic aircraft due to their ability to withstand high temperatures, increased toughness, and strength against ductility. Titanium-based materials are typically prime candidates for large-scale structural use within the framework and engines of such aircraft.

In space applications, magnesium alloys are fortified with graphite strands to create composites, particularly for scramjet engines where properties like light weight, high specific stiffness, and near-zero coefficient of thermal expansion are essential.

Figure 5 showcases examples of MMC applications, including missile fins, armors, and tank tracks, further highlighting the versatility and significance of MMCs in modern defense systems[43].

Figure 5 (a) Fin of guided missile, (b) Vehicle armour, (c) Tank Track

* **Electronics Components:**

Hermetic package materials are designed to safeguard electronic circuits from moisture and other environmental hazards. The glass-to-metal seals in these packages necessitate materials with an adjustable coefficient of thermal expansion (CTE). Aluminium-based metal matrix composites (MMCs) are well-suited for this purpose, as their CTE can be tailored based on the volume fraction of fibres or particles incorporated into the composite.

For instance, a copper-silver alloy matrix containing 55% by volume of diamond particles, known as Dymalloy, is employed as a substrate for high-power, high-density multi-chip modules in electronics due to its exceptionally high thermal conductivity. The ability to regulate the CTE of MMCs makes them ideal choices for hermetic package materials, ensuring the protection and reliability of electronic circuits under varying environmental conditions.

* **Sports Components:**

Sports equipment often requires materials that combine various types, such as metals, ceramics, polymers, and composite concepts. Creative design concepts are employed to fabricate these materials into the desired sports equipment. The use of metal matrix composites (MMCs) has been extensively studied in various sports equipment, including golf clubs, horseshoes, tennis racquets, and bicycle parts (frames, wheel rims, etc).

For sports bicycles, frames are commonly made from a mixture of aluminium, magnesium, titanium, and carbon fibre-based composites. Carbon-fiber-reinforced composites are the preferred choice for many sports equipment due to their high strength-to-weight ratio and toughness. These materials are particularly advantageous for achieving lightweight and high-performance sports gear.

****However, in some cases, aluminium and magnesium-based MMCs are also employed in sports equipment like tennis rackets, vaulting poles, and prosthetic limbs. These materials offer a cost-effective alternative while still providing the required performance and durability for specific sports applications. Overall, the use of MMCs allows for the creation of innovative and high-performing sports equipment to meet the diverse needs of athletes and sports enthusiasts.

Figure 6 (a) Prosthetic limbs, (b) bicycle frame, (c) Golf club

* **Space Components:**

Indeed, the extreme environment of space presents unique challenges that necessitate the development of new materials with specific properties. Spacecraft operating in near-earth orbit encounter a variety of naturally occurring phenomena, including vacuum conditions, thermal radiation, atomic oxygen, ionizing radiation, and plasma. Additionally, there are external factors such as micrometeoroids and human-made debris that spacecraft must withstand.

To withstand these demanding conditions, materials with high specific stiffness and low coefficient of thermal expansion (CTE) are essential. Specific stiffness relates to the material's stiffness-to-density ratio, making it crucial to have lightweight structures with high stiffness. A low CTE is essential to maintain dimensional stability and prevent distortion due to temperature variations in the harsh space environment.

Developing materials with these characteristics is critical to ensuring the reliability and longevity of space missions and spacecraft components. Advanced composite materials, like carbon-fibre-reinforced composites, and other innovative materials are often used to meet these demanding requirements in space applications. These materials play a vital role in the construction of lightweight, dimensionally stable, and high-performance structures for space exploration and satellite missions.

# Conclusion

Materials research in the field of light metal matrix composites (MMCs) has been highly active over the past two decades. The findings indicate that the major market for MMCs is currently the automotive industry, followed by electronics and thermal management systems. Continuous development in material and processing techniques has resulted in the creation of MMCs that are lighter in weight, more cost-effective, and offer higher performance for various applications. For instance, continuous fibre reinforced aluminium matrix composites are now used in specific aerospace applications that require high strength-to-weight and stiffness-to-weight ratios. On the other hand, particle-reinforced metal composites offer excellent specific strength and stiffness, isotropic properties, ease of manufacturing to near-net shape, outstanding thermal and electrical properties, and affordability. As a result, discontinuous MMCs find suitability in a wide range of applications.

The advancements in MMC technology have broadened the scope for their utilization across industries, including aerospace, automotive, electronics, and thermal management systems. The ongoing research and development efforts in this area continue to improve the properties and performance of MMCs, making them increasingly desirable materials for meeting the demands of various modern applications.

Significant advances in the development of fabrication routes for MMCs have played a crucial role in bringing down their production costs to acceptable levels. Researchers are continually working on refining the production methods of MMCs to enhance their performance, optimize their properties, and broaden their range of applications

As a result of these technological advancements, MMCs have found increasing applications in various industries. According to a global MMC market survey, a substantial growth of more than 20% in the usage of MMCs is predicted for the next two years. This indicates a growing demand for MMCs and reflects the increasing recognition of their benefits and advantages in various engineering and industrial applications. The continuous research and development efforts in the field are likely to further enhance MMC technology and expand their utilization in diverse sectors in the coming years.

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