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Metal Matrix Reinforcements - Fabrication, Applications, and Properties: A Review

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***Abstract*—Metal matrix composites (MMCs) have emerged as a transformational class of materials, demonstrating exceptional promise for increasing mechanical, thermal, and specialized characteristics across varied applications. This study gives a detailed assessment of current improvements in metal matrix reinforcements, concentrating on their effects, production processes, and applications. Particulate, fiber, and whisker reinforcements are examined for their influence on mechanical, thermal, and specialized characteristics. Various production processes, including solid-state fabrication and liquid-state fabrication, are examined. The evaluation focuses on applications in the aircraft and automotive industries. Addressing obstacles and future prospects in scalable manufacturing and innovative reinforcements, the article gives insights into the growing environment of metal matrix composites over the past years.**

Keywords: Metal matrix composites, reinforcements, properties, applications

I. Introduction

Metal, an important engineering element with a history of numerous technological uses, is currently being combined with ceramics to generate metal matrix composites (MMCs) due to developing scientific understanding and engineering demands. These composites meet special criteria in diverse applications that cannot be addressed by metal alone[1].

MMCs are metals combined with other metal, ceramic, or biological compounds. They are manufactured by spreading the reinforcements in the metal matrix. Reinforcements are frequently done to increase the qualities of the base metal such as strength, stiffness, conductivity, etc.[2] MMCs, as we know them now, have advanced rapidly throughout the past years. The greatest backing for these composites has come from the aerospace sector for airframe and spacecraft structures. More lately, the automotive, electrical, and recreation sectors have been working actively with these composites[3].

Reinforcement surfaces can undergo coating with either non-metallic or metallic materials. This is done to enhance adhesion (wettability), improve mechanical properties, and prevent undesirable chemical reactions between the matrix and reinforcement, especially at elevated temperatures[4][5]. Reinforcement types on metal matrices spanning from the broad classification of fibre and particle reinforcements to particular employing ceramics and carbon nanotubes[4].

There are several ways of coatings including Electroless Nickel Plating (EN), Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), etc. PVD is a process in

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which the condensed phase material penetrates a material phase of vapour with a thin film.[5] CVD is a deposition technology to chemically manufacture pure, high-performance solid materials. In Electroless Nickel plating (EN) technology, plating of nickel phosphorous alloy via the course of chemical reduction on the catalytic metallic surface[5].

II. TYPES OF METAL MATRIX REINFORCEMENTS

There are 3 major types of metal matrix reinforcements[6].

1. **Particulate**: This type of reinforcement uses particles, such as silicon carbide, aluminium oxide, titanium carbide, boron carbide, and carbon nanotubes. These particles are typically small and dispersed throughout the matrix.
2. **Fiber**: Continuous reinforcement uses monofilament wires or fibers, such as carbon fiber or silicon carbide. The fibers are embedded into the matrix in a certain direction, resulting in an anisotropic structure in which the alignment of the material affects its strength.
3. **Whisker/Discontinuous**: This type of reinforcement uses short fibers or particles, known as "whiskers." The most common reinforcing materials in this category are alumina and silicon carbide.

Other types of metal matrix composites include Hybrid reinforcements and Nano-reinforcements.

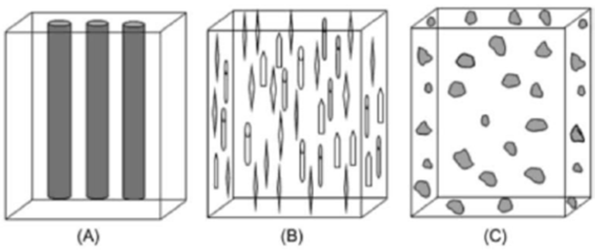

Figure 1.- Types of metal matrix composites (A) Fibre-reinforced MMC (B) Whisker-reinforced MMC (C) Particulate-reinforced MMC. [7].

III. PROPERTIES OF METAL MATRIX REINFORCEMENTS

The characteristics of metal matrix composites can be increased by the insertion of different reinforcements into the metal matrix. Some of the qualities that can be enhanced include[8][22][23].

- Strength: The inclusion of reinforcements can improve the strength of the composite material
- Hardness: The hardness of the composite material can also be improved by the use of reinforcements
- Stiffness: The stiffness of the composite material can be strengthened by the inclusion of reinforcements
- Wear resistance: The use of reinforcements can lessen the wear of the composite material
- Density: The density of the composite material can be lowered by the inclusion of reinforcements

Other properties that can be improved by reinforcement are Damping properties, corrosion resistance, fatigue resistance, creep behaviour, etc. The interface between the reinforcement phase and the matrix is crucial in optimizing features such as load transmission, wetting characteristics, reactions, and electrical conductivity[9].

A. Mechanical Property Enhancement

The incorporation of different reinforcements into the metal matrix boosts the strength, hardness, and stiffness, and lowers the wear and density of the materials[8]. The mechanical characteristics of MMCs can be increased by numerous means, including:

- **In-situ processing**: This involves chemical processes that result in the production of a reinforcing phase inside a metal matrix. The reinforcements can be generated in situ by chemical reaction or by physical mixing [10].
- **Green reinforcements**: These are ecologically friendly reinforcements that may be utilized to improve the mechanical qualities of MMCs. Examples of green reinforcements include natural fibers, such as bamboo, jute, and sisal, and recycled materials, such as waste tire rubber and waste glass [4].
- **Processing procedures**: The mechanical characteristics of MMCs can also be enhanced by refining the processing processes used to create them. For example, the adoption of powder metallurgical processes can result in MMCs with increased mechanical properties [4].

The reinforcement-matrix interface in MMCs is a key element in influencing the mechanical characteristics of these composites, including its influence on strength, stiffness, and toughness [6]. Therefore, it is vital to carefully select the type of reinforcement and processing method utilized to create MMCs in order to maximize their mechanical qualities.

B. Thermal Property Enhancement

Thermal or Thermo-physical properties refer to the properties connected to heat and temperature, including thermal conductivity as well as thermal expansion. These characteristics can be modified by several variables, such as the matrix material, reinforcement, and interfacial structure[11][12]. Some methods in which thermal characteristics can be increased include:

- *Thermal Conductivity*: The use of high thermal conductivity reinforcements, like graphene or bimodal SiC particles, can boost the thermal conductivity of the combination[12].
- *Coefficient of Thermal Expansion:* The relevance of the coefficient of thermal expansion (CTE) lies in applications such as vehicles, where materials with lower

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CTE are desired for dimensional stability. Research reveals that greater reinforcing percentage and higher graphite content lead to decreased CTE, stabilizing dimensions, refining grain structure, and boosting thermal conductivity using Carbon Boron Nitride (CBN) additions[13].

- *Thermal Insulation:* in MMCs, Thermal insulation is achieved by selectively selecting low-conductivity reinforcing materials, optimizing their dispersion and interface bonding, and designing the microstructure to inhibit heat transport. This design technique enables MMCs to efficiently lower thermal conductivity, making them attractive for different insulation applications[1].

IV. Thermal Reinforcers

MMCs may be reinforced with various materials to increase their thermal qualities. Here are some of the most widely utilized reinforcements for thermal characteristics improvement in MMC: [12][14].

1. Silicon Carbide: SiC is mostly used for reinforcing MMCs because of its high thermal conductivity and low coefficient of thermal expansion.
2. Alumina ($Al_2 0_3$): Alumina is another extensively utilized reinforcing material in MMCs for thermal characteristics augmentation. It has a high thermal conductivity and can improve the thermal characteristics of the composite.
3. Graphite: Graphite fibres that have high thermal conductivity, negative coefficient of thermal expansion, and are cost-effective are considered good reinforcements. When coated with Cr, these fibres exhibit in-plane thermal conductivity. Additionally, the infiltration of liquid copper into graphite foam produces a composite well-suited for heat sink applications.
4. Diamond: researchers have shown great interest in MMCs reinforced with Diamond because of their strong thermal conductivity and low coefficient of expansion

These amongst others are some of the materials mostly used in reinforcements of MMCs to improve their thermal properties.

V. Fabrication Methods

There are 3 main classes of fabrication methods namely:

- Liquid State Fabrication
- Solid State Fabrication
- In-situ Fabrication

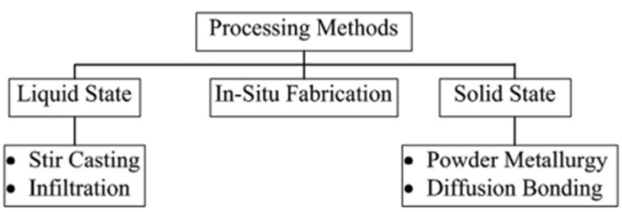

Figure 2. Classification of reinforced metal matrix fabrication methods[15]

A. Liquid State Fabrication

n this method, the metal is put in liquid or molten form and the reinforcements are integrated into it[16].

Types of Liquid State Fabrication

1) Stir casting

Stir casting (figure 3) is one of the most common and frequently used processes in which material creation (primarily Metal Alloys and Metal Matrix Composites) is carried out by melting metals and casting them to suitable shapes and sizes by pouring them into holes. It is also termed as liquid metallurgy[17].

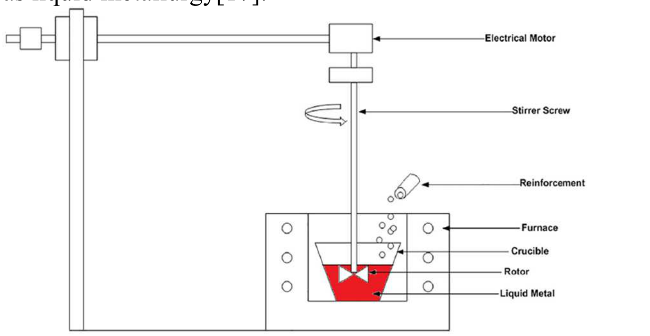

Figure 3. Stir casting process[15]

2) Infiltration

Infiltration (see Figure 4) involves filling holes in sintered metal utilizing liquid metal or alloy, in which the sintered metal is the matrix. Sintering compacts materials without melting them. Adding diverse materials strengthens the matrix, boosting characteristics for certain purposes)[16].

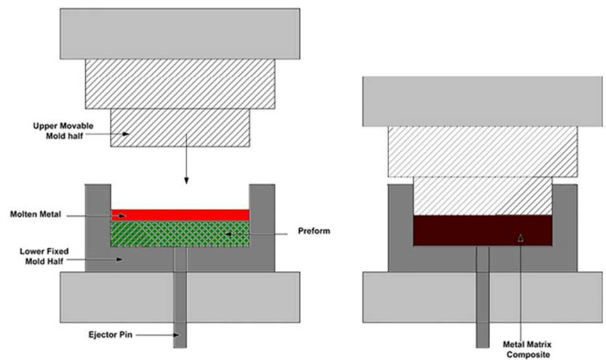

Figure 4. Infiltration process[15]

B. Solid State Fabrication

In this fabrication technique, bonding occurs between the metal matrix and the reinforcement phase resulting in the production of the MMC. It is usually done under high pressure and temperature thereby inducing bonding between the metal matrix and the reinforcement by means of mutual diffusion

1) Diffusion bonding:

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This process uses a metal matrix in the shape of foil and a reinforcement phase in the shape of long fibers. These are arranged on top of each other in a particular order and pressed at high temperatures. A material with a structure of laminate composite consisting of multiple layers is then obtained[10].

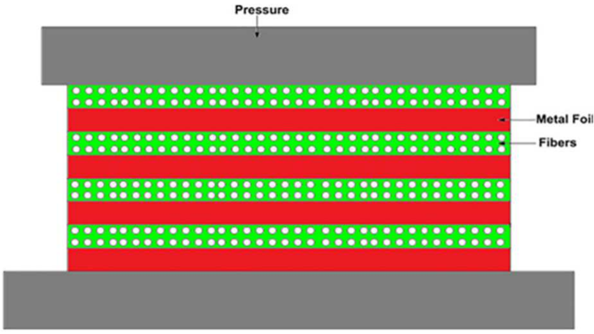

Figure 5.Diffusion bonding[15]

2) Powder metallurgy:

Powdered metal and discontinuous reinforcement are combined and then bonded by a process of compaction, degassing, and thermo-mechanical treatment (perhaps via hot isostatic pressing (HIP) or extrusion)

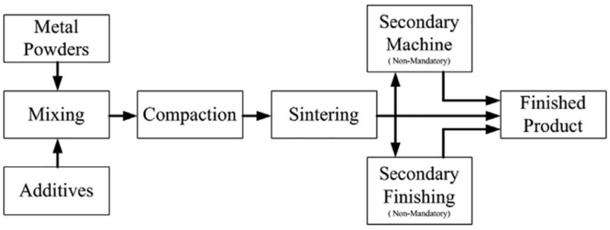

Figure 6.Powder metallurgy process[15]

C. *In-situ Fabrication*

In-situ fabrication of metal matrix reinforcements is a procedure in which scattered reinforcing phase is generated in the matrix as a result of chemical reactions during the composite manufacturing. In other words, the reinforcements are generated internally in the matrix during the composite fabrication. This technology is used to manufacture metal matrix composites (MMCs) with superior mechanical and tribological qualities[18][19].

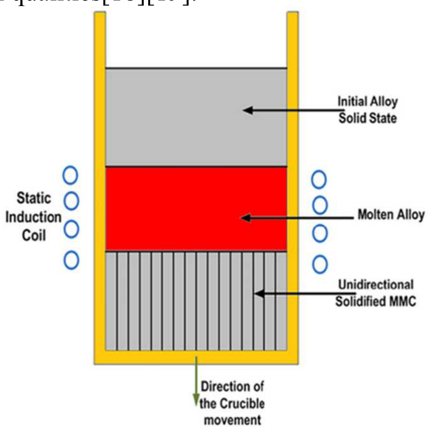

Figure 7. In-situ fabrication [15]

VI. ADVANTAGE OF REINFORCED METAL MATRIX OVER METAL MATRIX COMPOSITES

Metal matrix composites have a wide variety of applications the Aerospace and Automobile sector being its main one. This is because these industries require metals that are light yet high in strength. This makes the products functional and helps reduce its fuel intake[7][20]. Its use can be also be seen in bicycles, golf bats, electronic substrates, etc. For MMC like Graphene reinforced MMCs, it has the potential to also be applied in other industries like the chemical industry in addition to the others[21].

Reinforced metal matrix composites have several advantages over conventional metal matrix composites, including:[8]

1. Higher specific strength and stiffness are a result of the addition of high-strength fibres or particles
2. Improved wear resistance, thermal stability, and corrosion resistances
3. Modified properties such as damping capacity, ductility, and toughness
4. Enhanced interfacial bonding between the matrix and reinforcement, leading to enhanced load transmission and mechanical properties

Overall, the usage of reinforced metal matrix composites may result in materials with improved qualities compared to ordinary metals and metal matrix composites, making them appropriate for use in numerous applications, including aerospace, automotive, and electronic industries[2].

VII. CHALLENGES AND POSSIBLE SOLUTIONS

A. *Challenges of Metal Matrix Reinforcements:*

- **Weak interfacial bonding:** One of the issues with metal matrix reinforcements involves the weak bonding between the matrix and the reinforcement particles or fibers. This can lead to lower mechanical characteristics and performance of the composite material.
- **Degradation problems**: Reinforcement particles or fibers can interact electrochemically, chemically, or physically with the matrix, leading to numerous degradation difficulties such as corrosion or wear.
- **linking difficulties:** Joining metal matrix composites (MMCs) with other materials or even linking MMCs to themselves can be tricky. Fusion welding, for example, can lead to the development of undesired phases when the melting metal comes into touch and interacts with the reinforcement.
- **Low wettability:** In the manufacturing of particulate-reinforced MMCs, a typical difficulty is the low wettability of the reinforcement with the molten metal matrix. This might inhibit the regular dispersion of the reinforcing particles and alter the overall characteristics of the composite.

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B. Possible Solutions:

- **Improved interfacial bonding**: Researchers are researching numerous strategies to strengthen the interfacial bonding between the matrix and reinforcement, such as surface modification of reinforcement particles, employing interlayers, or adding nanoscale reinforcements.
- **Corrosion and wear protection:** Strategies to alleviate degradation concerns include utilizing corrosion-resistant reinforcing materials, providing protective coatings, or modifying the matrix composition to increase resistance to chemical or physical interactions.
- **Alternative joining methods**: Solid-state joining techniques, such as friction stir welding, have shown promise in addressing the problems inherent in fusion welding. These approaches can give greater control over the heat input and limit the production of unwanted phases.
- **Surface treatment and optimization**: Surface treatments of reinforcement particles or fibers can increase their wettability with the molten metal matrix, resulting to greater dispersion and bonding. Additionally, adjusting the composition and processing parameters of the matrix might optimize the wetting behavior.

It is crucial to note that the specific issues and solutions may differ based on the kind of metal matrix composite and the intended application. Ongoing research and development in this sector attempt to solve these problems and further improve the performance and dependability of metal matrix reinforcements.

VIII. CONCLUSION

In conclusion, this comprehensive study uncovered the revolutionary potential of metal matrix reinforcements, showing their vital role in boosting the mechanical, thermal, and specialized characteristics of composites. The research of particle, fiber, and whisker reinforcements has revealed their substantial impact on material behavior, resulting in better tensile strength, wear resistance, and other key properties. Moreover, the adaptability of metal matrix composites extends to varied production processes, ranging from liquid-state procedures to solid-state approaches like in-situ fabrication. These fabrication procedures give engineers with useful tools for modifying material qualities to meet specific application needs.

As noted in the discussion of applications, reinforced metal matrix composites display significant potential in a wide array of sectors, including aerospace and automotive industries, where better qualities translate into more efficient and durable components. The advantages of reinforced metal matrix composites over standard materials are clear, they exhibit heightened mechanical strength and thermal stability, traits crucial for pushing the frontiers of modern engineering. However, it is necessary to recognize the obstacles in scale production and cost-effectiveness that necessitate coordinated efforts in research and development. Overcoming these barriers would surely open the way for the larger usage of reinforced metal matrix composites in actual applications, significantly improving the area of materials science and engineering.

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