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Metal Matrix Composites: Innovative Materials for Molding the Future

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Abstract- Research on composite materials has gradually replaced traditional materials and alloys in an effort to create effective and cost-effective solutions for a range of applications. Metal Matrix Composites (MMCs) offer several benefits over traditional composites, including a lower thermal expansion coefficient, improved resistance to wear and abrasion, a higher strength-to-weight ratio, and reduced density. This review focuses on MMCs based on aluminium, magnesium, copper, titanium, and zinc as well as their alloys. It examines their physical and mechanical properties, manufacturing techniques (such as in-situ, liquid-phase, and solid-phase manufacture), and recent advancements. The properties of MMCs have been enhanced. As a result, they are suitable for critical applications in electronics, autos, and aerospace. Significant findings show how they can overcome the shortcomings of conventional materials by improving a range of mechanical properties. Their tensile characteristics, density, thermal expansion coefficient, elasticity modulus, hardness and fracture resistance, fatigue resistance, creep stiffness, and electrical conductivity can all be enhanced by using reinforcing techniques. The text also emphasises how important it is to select the right production processes to obtain the necessary characteristics while lowering costs and defects. This evaluation is a comprehensive resource for researchers and business professionals. It highlights current advancements, challenges, and the vast potential of MMCs as future resources.

Keywords- Metal matrix composites · Conventional materials · Fabrication techniques · Reinforcement.

I. INTRODUCTION

MMCs, or metal matrix composites, are becoming increasingly important in a number of industries due to their superior properties over conventional materials. These materials consist of two or more parts. Usually, a metal or alloy serves as the main component. It is reinforced with cellulose, particles, or whiskers to achieve better attributes than the individual components [1]. The primary goal of MMC production is to improve the characteristics of conventional metals by substituting inefficient materials with MMCs [2]. They provide typical tensile strength, wear resistance, yield strength, superior stiffness, thermal stability, and low density.

Table 1 Comparison of tensile strength (GPa), shear modulus (GPa), Young's modulus (GPa), density (g/cc), thermal expansivity (10–6/°C), Poisson's ratio, ductility (%), and yield strength (MPa) of metals commonly used as matrix material [7]

Material	Tensile strength (GPa)	Young's modulus (GPa)	Shear modulus (GPa)	Density (g/cc)	Thermal expansivity (10^{-6}/°C)	Poisson's ratio	Ductility (%)	Yield strength (MPa)
Aluminum (Al)	0.07–0.55	68–82	25–40	2.5–2.9	22–24	0.33	1–44	30–500
Copper (Cu)	0.2–0.4	110–130	40–50	8.93–8.94	16–17	0.34	3–50	50–400
Magnesium (Mg)	0.07–0.25	42–47	16–18	1.74–1.95	26–28	0.30	3.5–18	50–200
Nickel (Ni)	0.5–1.2	200–210	75–80	7.75–8.65	13–14	0.31	0.5–60	100–600
Steels (Fe)	0.4–2.5	200–210	70–85	7.1–8.0	11–13	0.30	18–31	240–690
Titanium (Ti)	0.24–1.0	90–120	42–45	4.4–4.8	8–10	0.34	1–40	250–1250

These characteristics make them perfect for the electronics, automotive, and aerospace sectors [3–6]. The essential mechanical and physical characteristics of metals frequently utilized in MMCs are compiled in Table 1. Tensile strength, Young's modulus, density, ductility, yield strength, and thermal expansion coefficients are some of these characteristics [7].

Composites composed of billet aluminum (Al), normal magnesium (Mg), zinc (Zn), excellent titanium (Ti) alloys are attractive choices for lightweight constructions in military, robotics, aerospace, as well as automotive industries due to their superior durability against wear, excellent tensile strength, and modulus. MMCs composed of steel, silver (Ni), and Cu (standard) copper alloys are advised for heavy industries, electronic packaging, and tooling [8–13]. From roughly 5496 masses in 2012 to over 9500 tons in 2023, the demand for MMCs grew globally [14]. As shown in Fig. 1, it rose progressively. Nevertheless, the development and application of MMCs face certain challenges. One of the primary issues is to achieve a homogenous reinforcement distribution inside the matrix. Other challenges include strengthening the bond between reinforcement & matrix and minimizing the formation of cavities during production. Selecting the appropriate production method is also crucial to ensuring that the final product has the attributes needed for specific applications. In recent years, a variety of MMC fabrication processes have been developed. These comprise liquid-phase manufacturing (such as stir casting and atmospheric pressure infiltration), solid-phase manufacturing (such as powder metal metallurgy and electromechanical alloying), and in-situ manufacture. Every strategy has advantages and disadvantages. Stir casting, for example, is cost-effective and suitable for large-scale manufacturing, but it struggles to distribute reinforcements uniformly. Powder metallurgy ensures outstanding characteristics despite its high cost. By contrasting these methodologies, engineers and researchers can choose the most effective ones for different applications.

The kinds, microstructural research, characteristics, production techniques, and uses of MMCs are all covered in separate sections of the manuscript. After an introduction, the mechanical and physical features are examined, and then the methods and mechanisms that cause wear are discussed. Liquid, solid, & in-situ fabrication techniques are all covered in detail. The report also discusses future research gaps and highlights technology applications and recent research. This review's main goal is to provide an overview of MMC advancements. The review demonstrates how crucial MMCs are to satisfying industry demands for high-performance, sustainable materials. It also highlights areas that still require work. The study offers useful information that can help researchers optimize MMCs for a variety of applications and determine future research objectives by addressing these features.

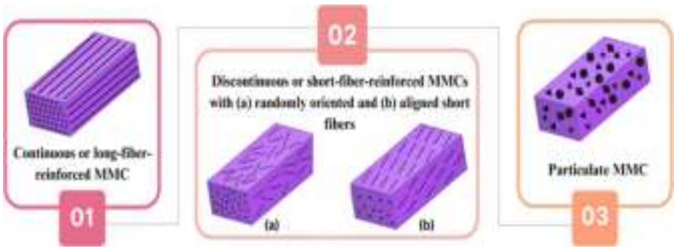

Fig. 2 Types of metal matrix composites (MMCs) based on the kind of reinforcement used [15]

II. TYPES OF METAL MATRIX COMPOSITES

Composites are frequently categorised according on the kind of reinforcements they include. The grid that holds everything in place includes these reinforcements. As shown in Fig. 2 [14–21], MMCs are often classified into three groups based on the type of reinforcement used: (i) continuous/long-fiber MMCs, (ii) discontinuous/short-fiber MMCs, and (iii) particulate MMCs. Table 2 lists a few popular forms of reinforcement along with their attributes.

Choosing the appropriate material for a particular application requires an understanding of the various types of reinforcement materials. Each variety has special qualities that make it appropriate for particular applications. Some typical MMC types and their traits are as follows:

Continuous/long-fiber metal matrix composites

This kind of metallic matrix composites (MMC) has long, uninterrupted fibres for reinforcements and a metal or alloy for the matrix material. The use of these long fibres as standard in several MMC applications has been extensively studied. But one of the biggest challenges in creating these composites is finding a balance between properties like ductility, mechanical strength, and toughness. This challenge limits the development and application of MMCs [15]. Smaller fibres, typically with a diameter of 5 to 30 µm, are sufficiently malleable to be handled in tows or bundles. These fibres, also known as multifilaments, are made of carbon, silicon carbide (SiC), or oxides. Multifilaments can be filament wound, braided, or woven. Conversely, monofilaments are fibres with larger diameters, around 100–150 µm.

In order to create monofilaments, silicon carbide (SiC) or boron, also known as B, are often deposited onto a carbon fibre or worthington (W) wire core using chemical vapour deposition (CVD). Because these individuals are less flexible than multifilaments, these fibres are usually used separately rather than in bundles. The strength of a continuous fiber-reinforced MMCs is determined by the direction of the load being applied, just as stiffness. When a fibre- reinforced composite material is loaded axially along the fibre orientation under iso-strain conditions, the substrate, fibre, and composites all experience the same standard amount of strain. The matrix, fibrous material, and composite all suffer the same amount of strain when a fiber-reinforced a conventional composite is compressed in the fibrous material direction under iso-strain conditions.

The following parameters are used to compute the Young's modulus of MMCs in the longitudinal path (Ecl, Eq. 1) and the transverse direction (perpendicular to the fibre direction) (Ect, Eq. 2):

Composite modulus in the longitudinal direction:

$$Ecl = Ef \cdot Vf + Em \cdot Vm \quad (1)$$

Composite modulus along the transverse direction:

$$\frac{1}{E_{ct}} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (2)$$

able 2 Characteristics of some common reinforcing materials

Metal	Density (g/cm^3)	Melting Point (Kelvin)	Modulus (Gpa)	Thermal Co	Thermal Expansion Coefficient	Properties	Applications
Aluminium oxide (Al_2O_3)	3.9	2323	410	25	8.3	High stiffness and excellent fatigue	Used in brake discs, pistons, cylinder heads, and engine connecting rods
Aluminium nitride (AlN)	3.25	2573	350	10	6	High thermal conductivity and elec-trical insulation. Exhibits superior thermal stability	Applied in electronic packaging, heat sinks, and high-power devices
Boron carbide (B_4C)	2.52	2723	450	29	5–6	Lightweight with a high melting point and excellent chemical resist-ance	Used in chassis, suspension compo-nents, lightweight armors, and fast breeder reactor components
Boron nitride (BN)	2.2	3273	90	25	3.8	Self-lubricating properties with high resistance to heat and wear	Used in crucibles, heat shields, and coatings in aerospace and electronics industries
Silicon carbide (SiC)	3.21	2573	480	59	4.7–5	High hardness, toughness, and resist-ance to wear and fatigue	Widely applied in pistons, propeller shafts, connecting rods, and brake rotors
Silicon nitride (Si_3N_4)	3.29	2173	310	29	3.3	High strength and remarkable tough-ness at high temperatures	Used in turbochargers, gas turbines, ceramic hybrid bearings, and auto-motive components
Titanium diboride (TiB_2)	4.5	3173	370	27	7.4	High elastic modulus, and wear strength resistance to high temperatures and abrasion	Used for ceramic cutting tools, ortho-pedic implants, and protective armor
Titanium carbide (TiC)	4.93	3413	320	29	7.4	High hardness, excellent wear resist-	Used in cutting tools, wear-resistant
			ance, and superior thermal stability				coatings, and aerospace components
Titanium nitride (TiN)	5.24	3223	600 29 9.4 High hardness, corrosion resistance, and excellent biocompatibility. Provides an attractive golden appearance				Widely applied in biomedical implants, decorative coatings, and tools requir-ing wear protection
Tungsten carbide (WC)	15.7	3073	690 110 5.2 Exceptional hardness, toughness, and				Used in cutting tools, mining equip-

where EmandEf is the stiffness of the matrix metal and fiber in the longitudinal direction, Vf is the volume fractions of fiber and Vm is the volume fractions of matrix metal with Vm equaling (1 −Vf).

Discontinuous/short-fiber metal matrix composite
This type of composite uses short, uneven fibres for reinforcement and a metal or alloy for the matrix. As shown in Fig. 2, there are two main types of short-fiber MMCs: (i) randomly positioned and (ii) aligned. The uneven form of the short fibres in these composites results in a complex fracture strength. Usually produced by melt infiltration, these fibres feature a fine-grained polycrystalline microstructure. Using single crystals instead of crystalline fibres may enhance mechanical characteristics since they are stronger as well as more resilient to mechanical stress [15, 16].

The adapted modified Shear-Lag (MSL) model can be used to predict the stiffness of short- and short-fiber MMCs [17, 18]. The MSL mathematical formulas (Eqs. 3, 4, 5, 6, 7, 8, and 9) take into account several factors, such as the whisker radius, unit of cell radius, fibre aspect ratio,, and Young's modulus, respectively, for both the whisker and matrix.

$$\frac{E_c}{E_m} = \frac{V^w E^w}{E^m} + \frac{V^m \cdot B}{E^m s^c}\sinh(ns) + V^m + \frac{V^g}{E^m \cdot s^c \cdot n^f s^f}\, A^f\ \cosh\ n^f s^f\ - 1\ + B^f \sinh\ n^f s^f \tag{3}$$

$$n^2 = \frac{E^m}{E^m(1+\nu^m)\ln\ \frac{R}{r}} \tag{4}$$

$$n'^2 = \frac{1}{(1+\nu^m)\ln\ \frac{R}{r}} \tag{5}$$

$$A = 0 \tag{6}$$

$$B = \frac{(E^w - E^m)\cdot s^c}{\cosh(ns) + {}^{n}\!/_{n^f}\sinh(ns)\coth(n^f s^f)} \tag{7}$$

$$A = -B \cdot \tanh\ ns \tag{8}$$

$$B^f = -B\ {}^{n'}\!_{n^f}\ \sinh(ns)\coth\ n^f s^f \tag{9}$$

The variables r and R stand for the whiskery diameter and unit cell radius, respectively. The variables s and sf represent the fibre aspect ratios. Ec is the composite, Ew is the whisker, and Em is the Young's modulus of the matrix material. sc is the strain in the composite. vm is the matrix's Poisson's ratio. Vw and Vg are the volume fractions of the whisker and the fictitious fibre,, respectively.

Particulate metal matrix composites (MMCs)
Particulate MMCs comprise reinforcing materials that are rough and equiaxial in shape, with an aspect ratio lower than 5. Their diameter is frequently greater than 1 μm, and they can possess either a crystalline mono- or poly-crystalline structure. In Figure 2, particulate MMCs are shown schematically. The most common type of composite is one that combines silicon carbide (SiC) with aluminium oxide (Al_2O_3). The compounds that are presently under investigation include titanium diboride (TiB_2), a titanium carbide (TiC), the zirconium (ZrO_2), a form of (BN), tungsten carbides (WC), and titanium dioxide (SiO_2). Particulate MMCs are typically made via casting, powder mixing, or consolidation [4,5, 19].

III. MICROSTRUCTURAL STUDY OF THE METAL MATRIX COMPOSITES (MMCS)

A metal matrix composites (MMC) is a microstructure that is created when metallurgical matrices are mixed with reinforcing phases such as ceramic elements, fibres, or whiskers. A MMC's microstructure has a significant impact on its mechanical, thermal, structural, morphological, and tribological characteristics and how well it performs in various technological applications. The metallic matrix typically provides ductility, rigidness, and thermal conductivity; reinforcement enhances strength, elasticity, and wear resistance. When the composite is microstructurally examined, details about its structure, material composition, morphology, and sample characterisation can be better understood. Table 3 provides a list of potential tests that could be used to achieve this.

An important factor influencing the composite's overall performance is the reinforcement's size, distribution, and interface bonding within the matrix. The isotropic qualities and reduced stress concentrations that can cause early failure are guaranteed by a uniform distribution of reinforcements.

Reinforcement distribution

The reinforcing phase, sometimes made up of particles (such as SiC or Al_2O_3), fibres, or whiskers, is included within the metallic matrix (such as magnesium, aluminium, or titanium). It is critical to provide isotropic properties by uniformly dispersing reinforcement, since clustering and agglomeration can lead to elevated stress levels and localised failures. For homogeneity, powder-based methods in metallurgy, for example, yield a more consistent dispersion than stir casting and other liquid-state processes [25].

Grain refinement

Grain refining in the metallic matrix is aided by reinforcements in MMCs via processes such as and suppression of grain development. Strength and hardness are two mechanical qualities that are improved by fine grain structures through processes like Hall-Petch strengthening [26].

Interface characteristics

The interaction between the matrix and reinforcement is vital for mechanical behaviour and load transfer. A strong and perfect interface ensures that stress is distributed efficiently. However, during high-temperature processing, it is typical for surfaces to bind excessively or for brittle intermolecular compounds to form, reducing ductility and toughness [27].

Defects and porosity

Mechanical performance of MMCs is negatively impacted by microstructural flaws, which include voids, porosity, or weak interfacial connections. Inadequate matrix infiltration into the reinforcing phase or insufficient consolidation during processing are common causes of these flaws. Improving the dependability of MMCs is the goal of modern manufacturing procedures, which attempt to minimise such defects.

Tailored microstructures

Modern fabrication techniques, such as nanoscale reinforcements and additive manufacturing, allow for fine-grained control over microstructural properties. Composites with enhanced interfacial properties, finer grain sizes, and more uniform reinforcement distribution can be mass-produced using these techniques [28].

Table 3 Microstructural study of the metal matrix composites

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Technique name	Description and characteristics	References
Energy dispersive X-ray spectroscopy (EDS)	The crystal system of material, characterization of the sample	[20]
Optical microscope (OM)	Size, morphology, and texture of materials, Resolution: 0.2-0.7 μm	[21]
Scanning electron microscopy (SEM)	Size, morphology, and texture material of materials, the 3D image of the surface of the sample, Resolution: 50-100 nm	[22]
Transmission electron microscopy (TEM)	Size, morphology and texture of materials, 2D projections of the sample, Resolution: 0.2-10 nm	[23]
X-ray diffraction (XRD)	Identify single crystals, and reveal the structure of crystals, Resolution: 11-13 nm	[24]

IV. PHYSICAL AND MECHANICAL PROPERTIES OF METAL MATRIX COMPOSITES (MMCS)

The presence of reinforcements causes composites made from metal matrix (MMCs) to display unique mechanical and physical characteristics. Composites' physical and mechanical characteristics are affected by a myriad of elements, including the interface between the matrix and reinforcement, the amount of voids, the shape of the reinforcement, the volume percentage, the geometry, the distribution, and the manufacturing process. In what follows, we will have a quick look at what makes MMCs unique.

Volume and weight fractions

Partitions by volume and weight indicate the percentage of reinforcing particles in the matrix. In order to estimate the mechanical properties of composites, it is essential to evaluate the reinforcement to matrix ratio. In terms of strength, rigidity, and resistance to wear, higher reinforcing fractions are preferable. On the other hand, clustering and decreased toughness might result from excessive reinforcing. The expression that follows (Eq. 10) can be utilised to formulate the relationships between mass and volume fractions:

$$W_m = \frac{\rho_m}{\rho_c} V_m \quad and \quad W_r = \frac{\rho_r}{\rho_c} V_r \qquad (10)$$

where WmandWr is the weight fraction of matrix and reinforcement material,VmandVr is the volume fractions of matrix and reinforcement material, ρc, ρm, and ρr is the densities of composite, matrix, and reinforcement material, respectively.

Density

The reinforcement causes MMCs to typically have more dense structure compared to the base matrix. Materials that serve as reinforcements, such silicon carbide (SiC) and aluminium oxide (Al2O3), raise the density, whereas particles with a lower density, like graphite, lower it. The rule of combinations can be used to calculate the density of MMCs. Equation 11 illustrates how the volume and density of the matrix and reinforcing elements are taken into consideration by this rule:

Or alternatively,

$$\rho_c = \rho_m V_m + \rho_r V_r \qquad (11)$$

$$\rho_c = \frac{1}{\frac{Wm}{\rho_m} + \frac{Wr}{\rho_r}} \qquad (12)$$

the densities of the matrix, reinforcement material, and composite are represented by ρm, ρr, and ρc, respectively. The matrix volume fraction is Vm, while the reinforcing material volume fraction is Vr. The weight fraction of the matrix material is Wm, while the weight fraction of the strengthening element is Wr.

Coefficient of thermal expansion (CTE)

Unreinforced matrices have a higher CTE than MMCs. Silica carbide (SiC) and aluminium oxide (Al2O3) are examples of reinforcements that act as thermal expansion restrictors. Dimensional stability is improved in high-temperature applications by this characteristic. The most problematic issue is when there is a difference in the thermal expansion of the composite. Differences in the matrix's and fibres' coefficients of the thermal expansion (CTE) are the main culprits here. Even when the temperature remains constant, thermal stresses will still be present in the volume of a composite. Contrarily, by achieving the correct distribution of fibres via matrix, one can manage the thermal expansion properties of a composite [29].

The CTE of a composite material can be calculated as (Eq. 13) [30]:

ac = amVm + ar Vr (13)

where αc, αm, and αr represent the CTE of the matrix, reinforcement, and composite materials, respectively. For both of the longitudinally (along the fibres, Eq. 14) and transverse (perpendicular to the fibres, Eq. 15) directions, the following formula can be used to obtain the CTE for continuous fibre reinforced MMCs:

CTE along the longitudinal direction,

$$\alpha_{cl} = \frac{\alpha_m E_m V_m + \alpha_f E_r V_r}{E_m V_m + E_r V_r} \qquad (14)$$

CTE along the transverse direction,

act = 1 + Vm am + af Vr (15)

where EmandEr is the elastic moduli of the matrix, and reinforcement material, respectively.Vm is the Poisson's ratio of the matrix.

Likewise, the Turner model [31] may also be used to determine the CTE for particle-reinforced MMCs (Eq. 16).

$$\alpha_c = \frac{\alpha_m K_m V_m + \alpha_f K_r V_r}{K_m V_m + K_r V_r} \qquad (16)$$

where Kr and Km is the bulk modulus of reinforcement and matrix, respectively.

Elasticity Modulus

One measure of a composite's rigidity is its elasticity modulus. Composites' elastic characteristics are affected by the kind, orientation, volume percentage, and bonding between particles and the matrix. Adding reinforcement usually makes the composite's elastic characteristics better [30].

The elasticity modulus of an MMC can be calculated using the equation (Eq. 17) as follows:

$$E_c = E_m V_m + E_r V_r \quad (17)$$

Along the transverse direction (Eq. 18):

$$E_{ct} = \frac{1}{\frac{V_m}{E_m} + \frac{V_r}{E_r}} \quad (18)$$

this is where the matrix's modulus of elasticity (Em) and the reinforcing material's modulus of elasticity (Er) are defined. The matrix volume fraction is denoted as Vm, while the reinforcement material volume fraction is denoted as Vr.

Eq. 19 provides the formula for calculating the elasticity modulus of composites supplemented with slender fibres and particles (aspect ratio-s) in the following way:

$$E_c = \frac{E_m(1 + 2sqV_r)}{1 - qV_r} \quad \text{where, } q = \frac{\frac{E_r}{E_m} - 1}{\frac{E_r}{E_m} + 2s} \quad (19)$$

Tensile strength

When compared to their unreinforced matrix metal counterparts, MMCs show superior strength. The strength of MMCs can be calculated as follows (Eq. 20):

$$\sigma_c = \sigma_m + \sqrt{\Delta\sigma_i^2} \quad (20)$$

when "Δσ" represents the contribution of different strengthening processes. The matrix strength is denoted by σm and the composite strength is represented by σc.

Load transfer

When a matrix can transmit stress to reinforcements, this process is called load transfer. According to shear-lag theories [26, 32], the matrix's strength is enhanced when stress is transferred from the matrix's pliable and softer material to the reinforcement's harder and more rigid structure. Here is an expression for it (Eq. 21):

$$\Delta\sigma_{LT} = V_r\sigma_m \frac{(L + t)AL}{4L} \quad (21)$$

where σm is the matrix yield strength, and σLT is the dimensions of reinforcement material in terms of length and thickness.

Thermal residual stresses

Compressive residual stresses are caused by the matrix's and reinforcement's different rates of thermal expansion. Crack propagation is prevented by these forces. The following relation (Eq. 22) [33] can be used to calculate the strengthening contribution due to thermal cycling at elevated temperatures. Cracks can form when residual tensions are high.

$$\Delta\sigma_{Ts} = \frac{E_r E_m}{E_r V_r + E_m V_m} V_r \Delta\alpha\Delta T \quad (22)$$

the matrix's Young's modulus (Em) and the reinforcement's Young's modulus (Er), the matrix's volume fraction (Vm) and the reinforcement material's volume fraction (Vr), the CTE mismatch (Δα) and the temperature differential (ΔT) are all variables in this context.

Orowan strengthening

Materials that are enhanced by dispersion can be described by the Orowan mechanism. The dislocation motion is limited in this mechanism by fibres or particles [30, 34]. The yield and tensile strengths of materials are improved by this method. Those MMCs that have fine reinforcements will see the most improvement. The size and dispersion of the particles determine the efficiency of this mechanism. (Eq. 23) gives the strengthening as a result of the Orowan mechanism:

$$\Delta\sigma_{OR} = \frac{0.13bG}{d_r\left[\left(\frac{1}{2V_r}\right)^{1/3} - 1\right]} \ln\frac{d}{2b} \quad (23)$$

in which G is the matrix's shear modulus. B is the vector of Burgers. You can think of dr as the diameter of the reinforcement. The reinforcing material's volume fraction is denoted as Vr.

Grain refinement strengthening

Because there are more grain borders in order to withstand dislocation motion, grains that are smaller increase strength. The strength of the yield is enhanced because dislocations are constrained by the bigger grain boundary areas. According to the Hall-Petch equation (Eq. 24), the relationship between grain size (d) and yield strength (σHP) is as follows:

$$\sigma_{HP} = \frac{K_y}{\sqrt{d}} \quad (24)$$

where Ky is the strengthening coefficient (which is a characteristic constant of each material).

Toughness and fracture toughness

The capacity of a substance to absorb energy and undergo plastic deformation without breaking is known as its toughness. This quality gives a ballpark estimate of the material's ability to withstand stress. The microstructure and composition of the matrix alloy, the kind of reinforcement, and the size and configuration of the reinforcement layer are the three primary parameters that establish the toughness of a matrix metal composite (MMC). Processing has the ability to alter microstructural features such as porosity, segregation, reinforcement distribution, and more [35].

Particles with fine (0.6 µm) in SiC/Al MMCs with different diameters of reconstituted SiC particles had significantly higher fracture toughness than coarsely ground particles (9.5 µm). Fracture toughness is 32.4 kJ/m2 for particles sized 42.1-32.4 kJ/m2 [36]. Crack initiation & fracture in SiC/Al MMCs comprising coarse particles were shown to be mostly caused by void development in the matrix around particular particles positioned at the primary crack point, as reported by Qian et al. [36]. Because of its importance in so many contexts, fracture toughness must be considered throughout the design and use of materials.

To ensure that particulate-reinforced MMCs meet code requirements, it is crucial to check the Plane-strain fracture resistance (KIC). These two metal standards, BS-7448 and ASTM-E399, are equivalent. After the plane-strain (KIC) test, the allowable toughness is determined by utilising the load-displacement curve. Fracture toughness is one criterion regarding material selection; it is affected by things like loading conditions and the material type. The higher the value, the less likely the subject matter is to crack under stress, making it ideal for applications where the strain is high. Equation 25 shows the provisional the durability of fractures (KQ) [37]:

function f an is a geometric function that expresses compliance according to the inverse relationship of crack length to width, where PQ is the load associated with a specific increase in cracked length, whereas W is the specimen's width, and B is its thickness.
W

IT IS IMPORTANT THAT YOU NOTE It is well known that ASTM E399 and BS 7448 are the two most popular ways to measure the fracture toughness of metals. The two significant distinctions lie in their testing methodologies. A standard developed by the American Society of Testing & Materials, or ASTM, for use in determining the linear elastic mechanical fracture mechanics approach for estimating plane-strain the endurance of fractures (KIC), ASTM E399 lays out the procedures. The J-integral & crack tip release displacement are defined in British Standard BS 7448, on the other hand.

Fatigue

Failure due to repeated loading is known as fatigue. In comparison to unreinforced matrices, the crack growth rate of MMCs is typically lower. The increased stiffness about the composite is responsible for the improved S-N curve behaviour under regulated cyclic loads or extreme cyclic fatigue. Figure 3 [38] shows the crack growth schematics (da/dN) for monolithic alloys and MMCs, with respect to the cyclic intensity component (ΔK). If the matrix alloy's particle size along with volume fraction were optimised, fatigue characteristics would be improved. Improved resilience to fatigue due to fine-particle dispersion.

Creep

The term "creep" describes a material's propensity to undergo persistent distortion under mechanical stress. As the temperature rises, it always climbs [38]. Reinforcements limit the movement of dislocations, which in turn decreases creep. The creep resistance of MMCs enhanced with ceramic particles is higher than that of base alloys.

The following is a basic governing equation (Eq. 26) of creep [39], which has been applicable over a broad range of stresses.

$$s_s = A \quad \sigma_a \; ^{2} \; \frac{-Q_{app}}{RT} \quad (26)$$

where εs is the steady-state creep rate, A is the a constant, σa is the applied stress, n is the stress exponent, Qapp is the the apparent activation energy, T is the temperature (in Kelvin), and R is the universal gas constant.

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V. WEAR RESISTANCE

When one surface interacts with another in relative motion, it gradually loses material, a process known as wear. The useful life and durability of materials are both reduced by wear. contacts between surfaces create it; these contacts might be abrasive, adherent, or fatigue-related. The process is heavily affected by variables like weight, speed, sliding interval, and surface type. In order to learn more about and improve the tribological performance of MMCs, researchers have studied them under a variety of circumstances. The main results on the wear characteristics of MMCs from several investigations are summarised in Table 4:

Corrosion resistance

In the course of normal reactions of chemicals with their surroundings, metals always deteriorate, a process known as corrosion. The presence of oxygen, water, or salts in the metal's environment might trigger this reaction. Typically, surface flaws like rust, pitting, or cracks appear, which eventually degrade the material. Corrosion resistance of MMCs is greatly affected by the type and quantity of reinforcement. Selecting the proper reinforcement and using the correct surface treatments are key to controlling corrosion in MMCs. Here are the main points from the investigations on the corrosion properties of Al-MMCs, as summarised in Table 5:

Electrical conductivity

An electrical conductivity test measures a material's ability to transport an electric current. A material's electrical conductivity is inversely proportional to its reinforcement volume %. Electric conductivity of MMCs is influenced by a number of variables, according to Weber et al. [53]. These variables include, but are not limited to, the matrix material, the type and dimension of reinforcement particles, as well as others. Reinforcing elements, such as graphite (Gr), raise conductivity, whereas ceramics (SiC, Al2O3) lower it. Here we observe, via instances, how different reinforcements influence the electrical conductivity of MMCs.

VI. ALUMINUM–SILICON CARBIDE (AL-SIC) COMPOSITES

Incorporating 10% SiC particles into an aluminium matrix can increase its electrical conductivity to approximately 28-30% IACS (International Annealed The use of copper Standard). The insulating properties of SiC particles cause a typical decrease in conductivity to 20-25% IACS when the SiC content is increased to 20%.

VII. COPPER-DIAMOND COMPOSITES

The values of electrical conductivity of aluminium matrix composites with diamond particles ranging from 40% to 70% IACS are quite impressive. Due to the very high conductivity exhibited by the copper matrix, the diamond particles, which are themselves non-conductive, improve a the thermal conductivity while preserving excellent electrical conductivity. In these cases, we see how the electrical characteristics of MMCs may be tailored to various electrical and electronic uses by adjusting the proportions and types of reinforcing elements.

Table 4 Wear Properties of Metal Matrix Composites (MMCs)

Table 4 Wear Properties of Metal Matrix Composites (MMCs)

Aspect	Key observations	References
Material Hardness	High-hardness materials reduce wear due to their strength and toughness	[40]
Reinforcement Effect	Increasing reinforcement fraction (wt./vol.) improves wear resistance but increases friction coefficient Reinforcements enhance stiffness and specific strength	[41]
Reinforcement type	Hard particles like SiC and Al_2O_3 improve wear resistance - Soft reinforcements like graphite enhance lubrication and reduce wear	[42]
Matrix-Reinforcement Bonding	Strong interfacial bonding reduces porosity, improves hardness, and enhances wear resistance	[43]
Composite Hardness	Reinforcement like Al_2O_3 and TiB_2 increases hardness linearly, reducing dislocation movement and enhancing wear resistance	[44]
Load and Wear Rate	Wear rate increases with higher loads, but incorporating reinforcements (SiC, Gr, Al_2O_3) reduces the rate (Excessive reinforcement can reverse wear reduction trends at higher loads.)	[45, 46]
Temperature Effects	Wear resistance decreases with higher temperatures as reinforcement bonding weakens -As TiB_2 reinforcement withstands wear up to 240 °C by resisting subsurface deformation. Above 240 °C, wear resistance drops due to softening of the matrix	[44]

Table 5 summary of the key findings about the corrosion properties of aluminum (Al-7075) MMC

Material/composite	Key observation	References
Laser-treated Al 7075 alloy	Laser treatment improves corrosion resistance. Nitrogen-treated samples perform best due to AlN phase formation (electrical insulator)	[47]
Al 7075 with Al_2O_3 particles	MMCs resist corrosion better than the base alloy but require control over solutionizing to avoid grain coarsening	[48]
Al 7075 in a thin electrolyte layer	Corrosion rate increases with longer immersion time	[49]
Al 7075 with Zr/TiO_2 particles	Adding TiO_2/Zr reinforcement improves corrosion potential but increases pitting damage at higher amounts in the case of TiO_2	[50, 51]
Anodized Al 7075 alloy	Anodizing and rolling improve corrosion resistance compared to the base alloy	[52]

VIII. RECENT RESEARCH AND DEVELOPMENTS ON THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF VARIOUS METAL MATRIX COMPOSITES (MMCS)

To find out if produced composites are good for certain uses, you have to evaluate their properties. In Table 6, we can see a summary of the most important results from current research on the mechanical and physical properties of various MMCs. Recent advancements in the field have shed light on how different reinforcement materials can enhance tensile strength, hardness, wear resistance, and copper, magnesium, and zinc matrices composites.

The results shown in the table highlight how MMCs have progressed significantly with the addition of different reinforcements. Because of these improvements, the com-posites are better equipped to overcome the drawbacks of base metals, expanding their potential uses.

IX. MODES AND MECHANISMS OF METAL MATRIX COMPOSITES (MMCS)

Metal matrix composites (MMCs) improve mechanical qualities by combining metal using hard ceramic particles; yet, this process results in heavy tool wear. This section incorporates research findings to describe the mechanisms involved in the various forms of wear that tools undergo while machining MMCs.

Edge chipping

When tiny bits of tool edge fall off while machining, it's called edge chipping. This is because the edge is subjected to intense tension or forces from impacts. Edge chipping caused considerable damage to Al2O3/TiC tools used to machine Al/SiC MMCs, according to Gallab and Sklad [77]. According to the research [78–80], the hard ceramic particles were responsible for the damage by chipping and creating grooves on the flank surface and cutting edge. Furthermore, as cutting rates were raised, chipping became more common.

Crater wear

The surface of a substance can develop a depression or pit called a crater as a result of wear. When workpiece and tool encounter friction or repeatedly touch each other, this happens. A study conducted by Gallab & Sklad [77] found that crater wear was caused by the removal of aluminium from the tool by the tougher SiC par-ticles within the workpiece. Titanium nitride (TiN) coated tools were more effective in reducing this problem. Sahoo et al. [81] did not see crater wear when turning A6061/SiC MMCs, suggesting that it would not be a major issue in all cases of MMC milling.

Notch wear

The flank face experienced notch wear because to the meandering ridges upon the machined surface, as reported by Ding et al. [78]. When comparing wet and dry cutting, they discovered that notch degradation was significantly worse with the former. Cutting temperatures were lowered by using coolant. Notch wear increased as a result of the workpiece matrix's increased hardness. Alternatively, notch wear was reduced at faster speeds because refrigerant was less effective at soaking heat. Nose wear was affected by the tool's toughness to abrasion and flank wear [82].

Flank wear

This is what happens when you use a cutting instrument frequently and wear down its flank or side. Flank wear became apparent at low cutting speeds during milling Al/SiC MMCs, as found by Manna and Bhattacharyya [83]. This happened because built-up edges and greater cutting pressures were to blame. As the cutting speed increased, the abrasive particles gained more kinetic energy, leading to an increase in flank wear (Gallab and Sklad, 1977). As the cutting depth was increased, flanker wear was also increased. Li and Seah [84] demonstrated that the tool life decreased as concentration of tough atoms in the matrix increased. Chemical evaporate deposition (CVD) enhanced tool wear rates while manufacturing silicon carbide (SiC) strengthened tools, according to Andrewes et al. [85].

Table 6 Overview of Studies on Metal Matrix Composites (MMCs)

MMCs type	Reinforcement material	Key findings	References
Aluminum metal matrix composite	Silicon carbide (SiC)	Increased density, tensile strength, and hardness with SiC fraction. However, a decrease in impact strength was observed	[54]
	Al_2O_3 and Al_4C_3	Improved compressive strength, hardness, and wear resistance with Al_2O_3/ Al_4C_3 addition	[55]
	Boron Carbide (B_4C)	Better interfacial bonding at lower temperatures (between 250 °C and 600 °C) while B_2O_3 formed at higher temperatures due to the oxidation process	[56-58]
	Titanium Carbide (TiC)	Increased density, hardness, and tensile strength with TiC fraction rise; reduced elongation and impact strength (by > 30%)	[59]
Copper matrix composite	Ceramic particles	Improved mechanical and wear properties compared to pure Copper	[60]
	Silver-reduced graphene Oxide	Increased microhardness, electrical and thermal conductivity with higher sintering pressure (from 30 to 50 MPa)	[61]
	Steel chips (5-10 wt%)	Increased tensile strength and density with steel chips; comparison with Al_2O_3 reinforced composite	[62]
	Titanium Carbide (TiC)	Increased hardness; reduced density and wear rate as the TiC content increased	[63]
Magnesium matrix composite	Silicon particulates	The wear mechanism shifts from abrasive to adhesive as the load and sliding rate increase	[64]
	$Mg_2B_2O_5$ whiskers	Improved mechanical properties like tensile strength and hardness	[65]
	Graphite	Increase in thermal conductivity with the addition of graphite particles	[66]
Titanium matrix composite	Silicon carbide (SiC) particulates	Increased hardness, wear resistance, and improved microhardness	[67]
	Boron carbide (B_4C)	increased hardness, reduction in wear rate with the inclusion of reinforcement	[68]
	TiBW / Ti64 network structure	Significant improvements in hardness and wear properties	[69]
	Ti64-(SiCF/Al_3Ti) laminated composite	Improved mechanical properties and suppression of micro-level crack development	[70]
Zinc matrix composite	Al_2O_3	Improved density, micro-hardness, and electrochemical properties	[71, 72]
	Silicon carbide (SiC) + graphite	Improved hardness and wear characteristics	[73]
	Chromium oxide (Cr_2O_3)	Enhanced thermal stability, microhardness, and wear resistance	[74]
	Graphite (1%, 3%, 5% by weight)	Increased corrosion rate with higher graphite content	[75]
		Better corrosion resistance with 1%	[76]

aluminum (Al) MMCs. A similar finding was reported by Ding et al. [78], Li et al. [86] and Kilickap et al. [87]. They observed that flank wear increased with cutting speed due to the thermal weakening of the binder.

Abrasion wear

When sharp particles on a workpiece's surface wear away tool material, this process is called abrasion wear. Mechanically moving hard particles over the tool area is the cause of this type of wear [88]. Gallab & Sklad [77] found that abrasion was the main cause of tool fatigue in Al/SiC MMCs, and Teti [89] found that the composites' anisotropy and lack of homogeneity made this effect much more pronounced. To address this, Lin et al. [86] detailed abrasion processes that include two or three bodies. The two-body abrasion process involves tough particles of ceramic in the workpiece cutting grooves into the tool surface. These grooves dictate the cutting direction. An errant ceramic particle undergoes three-body abrasion by means of tool and matrix material interactions [90, 91].

X. FABRICATION METHODS

The microstructure and characteristics of MMCs are greatly affected by the fabrication processes. A number of methods exist for mixing reinforcing elements with metal matrices in order to create composites with enhanced properties. First, treatment in a liquid state; second, treatment in a solid state; and third, processing in situ are the three primary varieties of these approaches. One must be familiar with these manufacturing techniques in order to optimise MMCs for particular applications and achieve desired material attributes. The selection of fabrication technologies is affected by many factors. Among these criteria are the features and distribution of reinforcements, in addition to their quantity and amount. It is essential to enhance the bonding and wetting of the matrix and reinforcement, while simultaneously preserving the reinforcement's strength and minimising damage. Factors like as cost of manufacturing, efficiency of the process, and product quality determine the optimal fabrication method. Some commonly manufactured MMCs and the methodologies employed by various investigations are displayed in Table 7.

Liquid state processing

A composite slurry is formed by dispersing reinforcing particles into a molten matrix in liquid-state processing; this slurry is then allowed to solidify into the desired shape. The reinforcement can be dispersed using a variety of processes, including melt infiltration, stir casting, compo-casting, melt deposition, and others.

Melt infiltration

Melt infiltration involves filling a porous preform with hot metallic material or alloy, either vacuum-filled or subjected to pressure. There is no external force required for the spontaneous flow of molten alloys such as Al-Si, Al-Zn, and Al-Mg into the reinforcing. Somatic infiltration is the term used to describe this phenomenon. On the other hand, mechanical force or atmospheric pressure can be used in forced infiltration to overcome resistance and ensure that the molten metal enters the porous structure. If the matrix and reinforcement are not well-wetted, the process will slow down and unwanted reaction products will be produced at the interface. Study after study has shown that activators as well as processing in an environment of nitrogen (N2) both improve wettability.

Silicon carbide (SiC) and a titanium carbide (TiC) are typical reinforcing materials that are heavily infused with aluminium (Al), Mg (magnesium), and alloys of these metals. Because of their low weight, excellent machinability, and resistance to corrosion, these materials find extensive use in the automobile sector. There is little effort and expense involved in this procedure. On the other hand, porosity and uneven reinforcing distribution are possible outcomes of the process. A decrease in mechanical strength [112] may result from these flaws. Below, we will quickly go over the three distinct infiltration processes.

Pressure die infiltration

The process uses die-casting technology to forcefully inject molten metal. Improved infiltration and reduced porosity are the results of this method. Mechanical forces produced by gas, vacuum, resonances, centrifugal forces, or electromagnetism are used to force molten metal into a die, as illustrated in Figure 4, according to references [113, 114]. To make uniform MMCs, the preform is filled with molten metal. It is quite challenging to position the preform correctly during penetration. The product's quality is affected when the process is moved.

Table 7 Some commonly fabricated MMCs through various processes

Sr. No	Matrix material	Reinforcement used	Preparation method	References
1	Nickel-Aluminides (Ni-Al) matrix	Titanium Diboride (TiB_2) particles as reinforcement	Spray deposition	[92-94]
		Chromium (Cr)/ iron (Fe)/ tungsten (W)/ molybdenum (Mo) as reinforcements	In-situ method	[95]
		fiber reinforcement of W/ Al/ Mo etc	Reactive infiltration	[96, 97]
2	Aluminium (Al) matrix	Titanium Dioxide (TiO_2) as reinforcement	Liquid powder metallurgy	[98]
		Silicon Carbide (SiC) as reinforcement	Vacuum pressure casting	[99]
		SiC particles and whiskers as reinforcement	Powder metallurgy	[100-102]
		mica and SiC as reinforcement	Stir casting	[103]
		SiC, Aluminium oxide (Al_2O_3), or Graphene particles as reinforcement	Spray deposition	[99]
3	Magnesium (Mg) matrix	SiC as reinforcement	Stir casting	[104]
4	Aluminium and Magnesium (Al-Mg) matrix	SiC as reinforcement	Pressure infiltration	[105-108]
5	Copper (Cu) matrix	Graphene particles as reinforcement	Stir casting	[109]
		steel reinforcement	Stir casting	[62]
6	Copper-Niobium (Cu-Nb) composites		Diffusion bonding	[110, 111]
7	Titanium (Ti) matrix	SiC fibers as reinforcement,	Vapor phase deposition	[92]

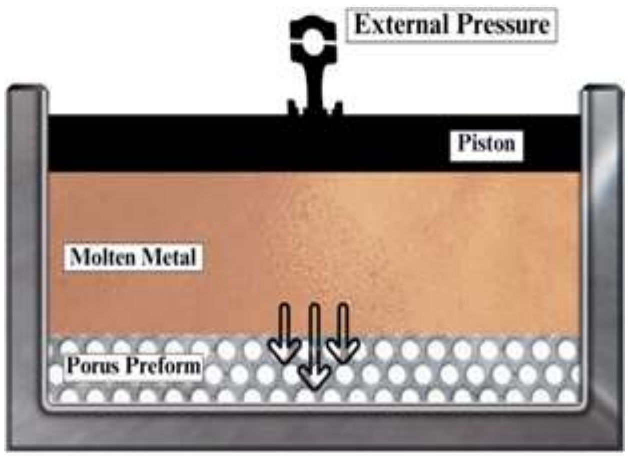

Fig. 4 MMCs preparations by pressure die infiltration process [115]

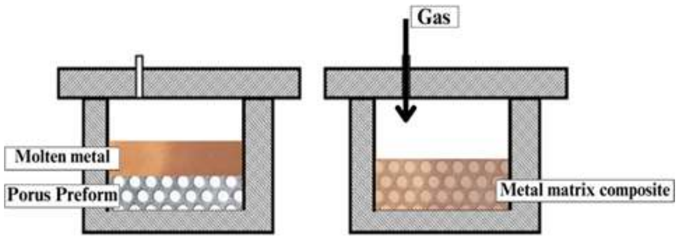

Fig. 5 MMCs preparation by gas pressure infiltration [115]

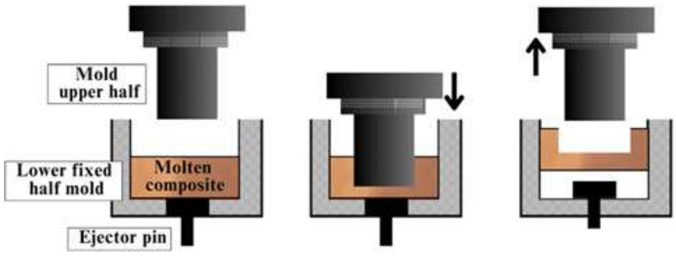

Fig. 6 MMCs preparation by squeeze casting infiltration [115]

compromised. The process is suitable for high-volume production. However, it requires precise control of pressure and temperature.

Gas pressure infiltration

This method involves injecting pressurised inert gas into reinforcement preforms. Reduced porosity and uniform infiltration are assured. To increase the gas pressure, you can either pressurise a melting bath before infiltration to push the molten material into the preform, or you can apply the resulting pressure immediately to the melt's surface after the preform is immersed in the resulting melt [116]. Figure 5 shows the gas pressure penetration method along with all of its components. You can achieve a smooth penetration and avoid trapped air by applying gas pressure from each other end within the preform. This approach is easier on fibres than others because of the shorter reaction times. Additionally, this approach works well for producing composites on a large scale.Is a report required before it can be removed?

Squeeze casting infiltration

The lower half of a permanently set mould is where the reinforcing phases, like as particles or fibres, are deposited in squeeze casting. Fig. 6 shows the process of pressing liquid metal into a preform while the upper moveable part of the mould slides downward. To reduce casting flaws like porosity and cracks, high pressure is used during the solidification process improves the matrix's adherence to the reinforcement. The short penetration length of this approach makes it efficient for reactive materials like magnesium (Mg) [117]. Crucial considerations in guaranteeing the high standards of squeeze moulded composite include mould and die temperature, time to pressurise melt, and pace of melt filling. The MMCs made using this method have superior mechanical characteristics. It ensures that there will be little to no porosity and that it will be wettable. Nevertheless, expensive moulds and presses with huge capacities are required.

The two main ways that pressure is applied in squeeze casting are the "direct" and "indirect" approaches. The preforms are infiltrated with molten melt by applying direct pressure to them in the direct process. Using a gate mechanism, the melt is forced into the preform in the indirect technique. Relatively simple tooling is used in direct-squeeze casting. Unfortunately, without a gate mechanism, the melt volume must be precisely determined. Indirect squeeze casting typically limits oxide residual in the composite, which is another downside of the direct method.

Ultrasonic infiltration

Ultrasonic infiltration refers to the process of making metallic matrix composites by incorporating ultrasonic vibrations into molten metal. This strategy ensures that the reinforced particles are dispersed more uniformly. In order to enhance the wetting process between the metal material and reinforcing particles, the oxide layer is removed from the exterior of the molten metal using ultrasonic waves. As a result, particle clustering is less likely to occur, and better bonding is guaranteed [118].

Increased tensile strength and enhanced resistance to wear are two examples of the mechanical qualities that benefit from this. This process works well for making composites that contain nanoparticles or other small reinforcing elements. Ultrasonic infiltration produces composites with superior bonding and fewer flaws as compared to other processes, such as stir casting, in terms of mechanical qualities. This is because there is a more uniform distribution of the reinforcing particles. Nevertheless, there are a few restrictions with ultrasonic invasion. Ultrasonic vibrations and exact regulation of processing parameters and temperature are essential to the operation, which necessitates specialised machinery. This leads to higher production expenses. The fact that it is batch-wise means it might not work for industrial-scale production.

Advantages, disadvantages, and applications of the melt-infiltration technique are summarized in Table 8.

Stir casting

Stir casting, sometimes called compo-casting, is a popular and inexpensive way to make composite materials. This process involves heating the base metal or alloy to a temperature higher than its melting point in a furnace, then pouring it into a crucible. After the matrix metal has melted completely, the reinforcing phase (fibres or particles) is mixed in using mechanical or ultrasonic stirring. The metal in a liquid state will be heated evenly if the mixture is stirred [119]. Figure 7 shows the stir-casting process. The efficient dispersion of reinforcement materials can be achieved by carefully adjusting agitation speed, duration, melt degree of temperature, and crucible size. Optimisation of processing settings allows for the uniform dispersion of particles with diameters ranging from 5-100 µm & up to 30 percent by volume. Wetting agents are used to the dispersed phases to improve interfacial bonding and to avoid unwanted reactions. As an example, Lai and Chung [120] discovered that brittle aluminium carbide (Al_4C_3) can be formed when silicon carbide (SiC) along with aluminium (Al) interact at high temperatures. According to [120], this formation affects the composite's mechanical characteristics. There are a number of advantages to the stir casting method. It works well for mass production and is cheap. Because of its simplicity and adaptability, it can accommodate a wide variety of reinforcement materials. But it's not always easy to distribute reinforcement evenly, and problems like particle clustering or settling are possible. Table 9 summarises some of the aspects of the stir casting method, including its benefits, drawbacks, and potential uses.

Melt deposition

The composite is formed by mixing reinforcements with molten metal and then solidifying the mixture using the melt deposition technique. This technique works well for manufacturing on a massive scale. Additionally, it guarantees that the matrix and reinforcement will bind well. But it's not without its flaws. It is possible for reinforcements to form clusters and lead to unequal distribution. The composite's mechanical qualities may be compromised as a result of this problem. On top of that, some reinforcing materials are vulnerable to heat damage. Composites with fibre reinforcement are typically created using deposition techniques such as electroplating, PVD, or chemical vapour deposition. Composites with metal matrix reinforcements, whether via particles or fibres, can be produced using spray or fragmented melt deposition [121].

Table 8 Advantages, disadvantages, and applications of melt-infiltration technique

Advantages	Disadvantages	Applications
Simple and economical Volume fraction is more Suitable for mass production	Restricted size and limited by preform shape Rarely achieves proper homogeneity Reaction between matrix and reinforcement can take place	Pistons, Cylinder Liners Brake Rotors and drums, turbine blades, Propeller shafts and impellers, Armor plating etc

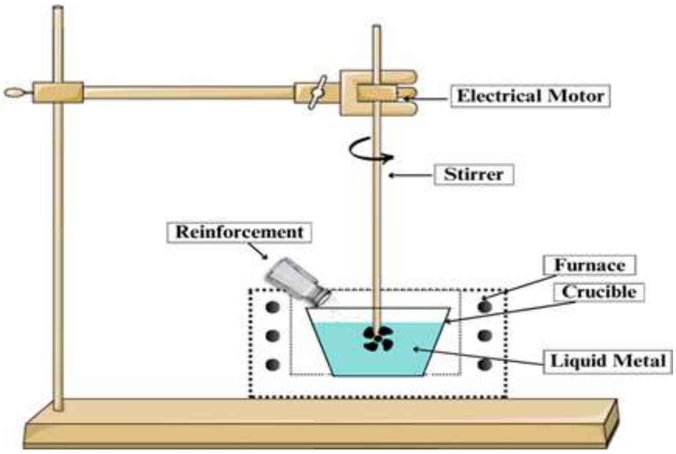

Fig. 7 MMCs preparation by stir casting method [115]

Electroplating/electrodeposition

Applying a current of electricity to an arrangement containing ions of the target substance allows electroplating or electrodeposition to deposit a layer of the matrix metal. Producing thin layered composite layers with superior surface characteristics is a common usage of this technology. Due to its mild operating temperature, it inflicts little to no harm on the reinforcing fibres. Coating complicated objects precisely is one of its main benefits. You can also adjust the coating's thickness and composition using this method. This method does produce MMCs, however they frequently have processing flaws such poor bonding and porosity. A restricted variety of alloy matrices is also outside the capabilities of this approach.

Electrodeposited composites outperform their non-deposited counterparts in terms of mechanical qualities such as wear and corrosion resistance. They work well in situations when improved surface properties are necessary.

Chemical vapor deposition (CVD)

By using chemical vapour deposition (CVD), a vaporised component that has been through a reaction of chemicals or breakdown can be applied to a substrate. A thick and uniform coating can be observed in the microstructure of a CVD-made composite. Strength and thermal stability are two areas where CVD composites really shine in comparison to other mechanical materials. They are perfect for these domains due to their aeronautical adaptability and outstanding performance. This method can be used to make a variety of carbide, oxide, oxide, nitride, or pristine metal coated precursor wires for building crystal-line or amorphous MMCs [122, 123]. The great wetting potential of coatings constructed of titanium diboride material (TiB2) makes them highly desired. The procedure is so time-consuming that mass production may not be possible

.

Physical vapor deposition (PVD)

The process of physical vapour deposition (PVD) involves vaporising a substance in a vacuum to create a thin coating. There are three main ways to classify PVD operations based on the methods utilised to produce vapour. Methods based on evaporation, sputtering, and ion plating are these. The use of electron electron beam evaporation and arc , laser ablation, and radiation heating are the evaporation-based methods. Varying methods of sputtering are used to vaporise coating materials [124-126]. argon gas plasma discharge for ion plating and subsequent deposition of vaporised components onto a sub-strate. There are no chemical reaction by-products produced by PVD, making it very versatile in coating formulations. It doesn't utilise any chemicals that are bad for the environment. The high cost and ineffective coating of big or irregularly formed components are two of PVD's limitations. While PVD composites are great for surfaces, they aren't practical for manufacturing large quantities of anything.

Spray deposition

Spray deposition involves spraying molten metal mixed with reinforcements onto a sub-strate. The process involves breaking up steam of molten metal into fine droplets using a high-speed jet of inert gas

Table 9 Advantages, disadvantages, and applications of the stir casting method

Advantages	Disadvantages	Applications
Larger size and extensive range of shape Affordable and suitable for large-scale manufacturing Less reinforcement damage and very high metal yield (>90%) Promotes better bonding between the matrix and reinforce-ment materials	Volume fraction ranges up to 30% Hard to attain uniformity Possibilities of reaction between matrix and reinforcement at high temperature	Aircraft wings, turbine blades, pistons, brake rotors, cylinder liners, and lightweight components for military vehicles

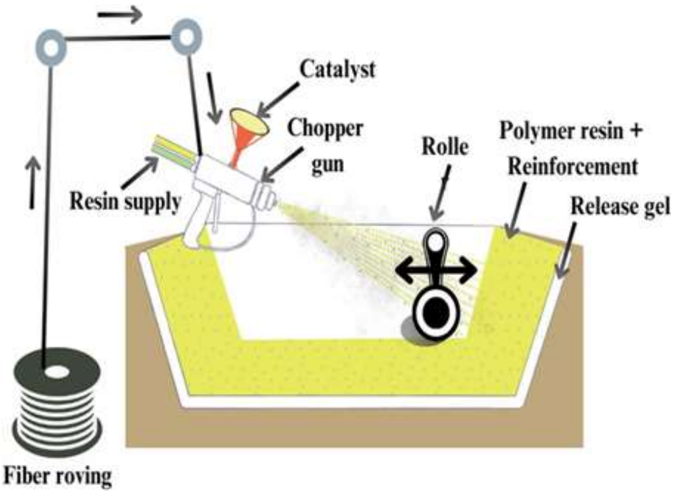

Fig. 8 Diagrammatic rep-resentation of the spray-up technique [127]

, most commonly nitrogen (N2) or argon (Ar). Sprayed with the reinforcing material and gathered on a substrate, these droplets have a size of 300 µm or smaller [127] (Fig. 8). The next step is to apply the suitable post-processing techniques to densify the depositions. This process results in tiny microstructures and quick solidification. To accomplish uniform reinforcement distribution, however, the process necessitates careful management. The high rate of material waste makes it less cost-effective for use on a smaller scale.

Grain refinement and defect reduction are hallmarks of the composites made via spray deposition. Comparatively, the mechanical characteristics are superior to those of melt deposition. There is also reactive spray-forming, which makes use of gas-liquid processes. Here, a reaction zone within the spray nozzle is used to inject gases into the liquid stream. This approach has been used to introduce oxide, carbide, nitride, cellulose, and silicide reinforcements into metal matrices [128, 129]. To obtain a uniform distribution of particles, it is vital to control the atomising and reinforcement feeding conditions. The spray-up process produces products with poor mechanical qualities and a high resin content, making them bulky. Table 10 enumerates the numerous benefits, drawbacks, and uses of this method.

Advances in liquid-state processes

The scalability, affordability, and adaptability of liquid state processing have made it a popular choice for manufacturing MMCs. Composites with improved mechanical and physical characteristics can be created by mixing reinforcing elements with molten metal using this process. More recent developments in liquid state processing have been made to address these issues, with the goals of achieving reinforcement uniformity, controlling porosity, and achieving strong matrix-reinforcement bonding. The improvements of MMC qualities that have resulted from recent advances in liquid-state processing are detailed in Table 11.

The potential uses of MMCs in sectors including aerospace, automotive, and defence might be greatly expanded with additional study into parameter optimisation and hybrid reinforcements for improved performance.

Solid state processing

Producing MMCs by solid-state processing eliminates the need to melt the metal matrix. When contrasted with liquid processing technologies, solid-state processing offers several advantages. This approach eliminates the possibility of problems like matrix-reinforcement reactions or porosity. For reactive systems, solid-state processing is the way to go. This approach relies on strong interfacial bonding and uniform reinforcement distribution to produce composites with mechanical characteristics. Having said that, they can be quite pricey. Powder metallurgy, mechanical alloying, deformation processing, and diffusion bonding are some of the most well-known solid-state processing methods.

Table 10 Advantages, disadvantages, and applications of spray-deposition technique

Advantages	Disadvantages	Applications
Metal yield is medium The process is simple and the tools are cost-effective The fiber and resin are deposited quickly Suitable for creating various coating	Products tend to be bulky due to the high amount of resin used The mechanical properties are not very good because the resin have low viscosity Often suffers from processing defects like poor bonding and porosity	Pistons, connecting rods, lightweight structural components in aerospace, electronic packaging, and wear-resistant coatings

Table 11 The advancements in liquid-state processing and their contributions to enhancing MMCs properties

Research focus	Improved properties	Year	References
Enhanced wetting and uniform dispersion in Al-SiC composites using ultra-sonic-assisted casting	Reduced porosity, improved hardness, and wear resistance	2019, 2020	[130, 131]
Liquid casting with pressure application, improving densification and reducing porosity	Application of pressure during solidification improved density and reduced porosity, yielding composites with better wear resistance	2020	[132]
Functional graded Al-SiC composites with layered reinforcement for automo-tive applications	Adding SiC to Al5083 alloy increases microhardness (55%), tensile strength (29%), and wear resistance (25%) compared to monolithic Al alloy	2018	[133]
Al-TiB_2 composites demonstrated high compressive strength and microhard-ness using squeeze casting	Adding Al-TiB_2 to molten Mg alloy improves hardness (16.1%), yield strength (53%), tensile strength (26.3%), and elongation (25.6%)	2018	[134]
Iron-based glassy particles in the Al matrix achieved exceptional flexibility and strength	Combined Fe_2O_3 and B_4C reinforcements in Al6061 alloy enhance mechanical properties, including tensile and compressive strength	2019	[135]

Iron-based glassy particles in the Al matrix achieved exceptional flexibility and strength Combined Fe_2O_3 and B_4C reinforcements in Al6061 alloy enhance mechanical properties, including tensile and compressive strength 2019 [135]

Powder metallurgy

A lot of MMCs are made using powder metallurgy. Combining metal or alloy powder with strengthening particles or whiskers is known as powder metallurgy. Ball milling is used to homogenise the mixture. The next step in turning the powder combination into a solid is to use a mould to compress it into the required shape while it is still at room temperature. The next step, after compacting the material, is to raise the temperature to a point where the powder particles fuse together without melting. The procedure for powder metallurgy is shown in Figure 9. This approach has the potential to treat copper (Cu), magnesium (Mg), and particle-reinforced aluminium (Al) [68, 136-138]. But because of the risk of damage from high pressure, they aren't good for long/continuous fibre reinforcement. Isostatic hammering (HIP) is used for long/continuous fibres [139, 140]. Despite the potential for unequal reinforcing distribution, it is inexpensive for mass production.

Impact resistance, a creep resistance, a and ductility are some of the qualities that are enhanced by this technique. The many benefits, drawbacks, and uses of this method are detailed in Table 12.

Mechanical alloying

To create a uniform material, mechanical alloying fractures, welds, and re-welds powders several times [141, 142] (Fig. 10). The process begins with the matrix and reinforcing ingredients being processed into fine powders in a ball mill. The powders are compressed by use of a heated isostatic technique. After that, the compaction-induced tension is removed via the sintering process. Nanocomposites can be made with its help because of a uniform arrangement of fine reinforcements it offers. Yet, the process can be laborious and lead to the introduction of contaminants as a result of extended milling. Although this process improves the hardness and strength of composites, residual stresses may still be an issue.

Attrition mills and other high-energy grinding tools are utilised in mechanical alloying. A rotor and a fixed drum make up this mill. A rotor is equipped with a set of arms or rotating impellers that are connected to a drive shaft. Impellers in the motor-driven rotor stir the powder and steel balls in the drum. Compared to traditional mills, this method can achieve speeds up to a factor of ten.

The particles go through a number of transformations while milling. The balls pick up various particles, smooth them out, smash them, and mix them with others. Every impact changes the particle's shape, exposing it to more surfaces that can oxidise. That is why a vacuum or inert gas atmosphere is ideal for milling, since it eliminates the need for air. The approach greatly enhances the dispersal of particles. Milling nickel aluminide (NiAl) and yttrium oxide (Y2O3) in the form of liquid nitrogen (N2) results in an ultrafine aluminium nitride (AlN) dispersion. "Cryomilling" describes this process.

In mechanical alloying, the goal is to create a homogeneous material by separating ground particles from unground ones. Another concern with the pulverising mill is the possibility of contamination from the vessel, hammers, balls, or surfactants. This pollution might happen as a result of chemical responses with the mill's environment. This is particularly important

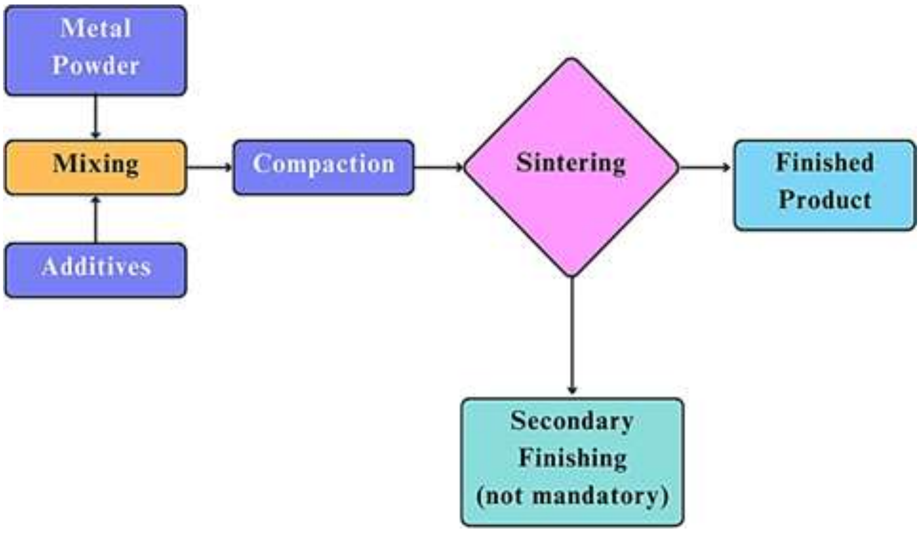

Fig. 9 The steps involved in MMC preparation by powder metallurgy [115]

Table 12 Advantages, disadvantages, and applications of Powder metallurgy

Advantages	Disadvantages	Applications
Very high metal yield and volume fraction range up to 30-70% Controlled porosity Controlled size and a wide range of shapes	Reinforcement fracture High costs due to expensive tooling and equipment Suffer from low ductility and strength Powder materials are very costly	Automotive brake discs, pistons, turbine blades, cutting tools, thermal management materials, biomedical implants, and high-performance sporting equipment

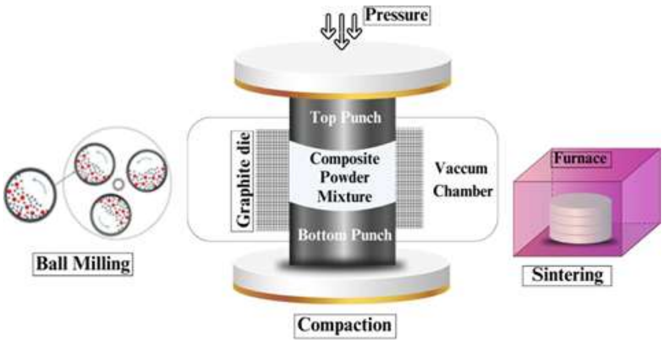

Fig. 10 MMCs preparation by mechanical alloying [143]

common when milling very hard materials. Proper care can reduce these issues to a minimum. The mechanical alloying process is relatively expensive which limits its industrial application [101, 102].

Diffusion bonding

One solid-state technique for combining a layer of reinforcing fibres with thin sheets of metal matrix material (called foil) is diffusion bonding. A sandwich-like structure is created by stacking layers of foil and fibre in alternate directions using this procedure. Pictured in Figure 11. The next step is to heat and pressurise the metal-fiber sandwich until it's hotter than the metal's melting point. Fabricating MMCs with intricate geometries is a good fit for it. While this approach guarantees effective interfacial bonding, it comes with several limitations, such as a relatively high time to process, cost, and the requirement for surfaces to be clean [144].

Interfacial interactions between the matrix and the fibre can occur due to the high processing temperatures used in the diffusion bonding process. The interface's durability and load-bearing capacity can be diminished as a result of these responses. It is common practice to apply coatings of antimony (Ta), niobium (Nb), or another metal at the interface of a fibre and matrix to rectify the problem of thermal expansion mismatch [145].

Uneven dispersion of fibres is one drawback of this method. Initiation of cracks caused by fatigue is one mechanical property that might be adversely affected by this issue. In addition, a vacuum is typically required for the diffusion process due to the oxidation tendency of the foil and metal coated surface, thereby rendering bonding more difficult. Despite these obstacles, diffusion-bonded composites with enhanced mechanical and physical characteristics at high temperatures are available, for example, aluminium (Al) or as titanium (Ti) alloys supplemented with silicon carbide (SiC) and boron (B) fibres [146]. Because of this, gas turbine engines are a good place to put them.

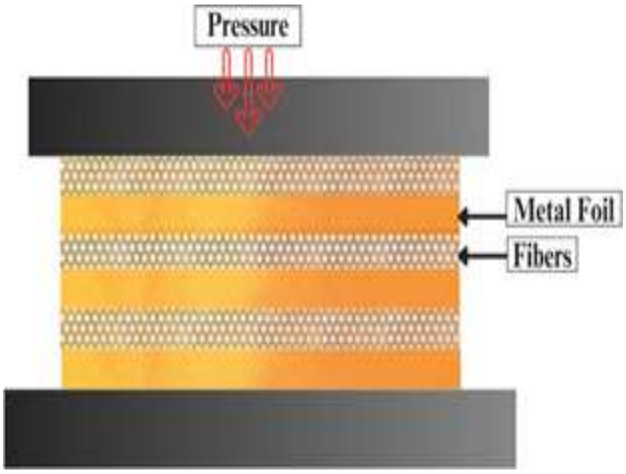

Fig. 11 Diffusion bonding [143]

Deformation processing

Extrusion and rolling are examples of deformation processing processes used to create MMCs. The microstructure of the matrix is refined by this method. Consequently, the composite's mechanical characteristics are enhanced. Additionally, they improve directional qualities by aligning reinforcements. The method for making sheet metal-composite laminates is illustrated in Figure 12 [92, 110, 111]. Here, mechanical deformation causes the minor phase of a two-phase alloy to stretch and create fibrous patterns inside the major phase's matrix. Because of their similar flow stress patterns, ductile materials are the only ones that can be deformed simultaneously using this method. To further decrease mechanical anisotropy, deformed materials must undergo heat treatments subsequent to processing [147, 148]. While deformation-processed MMCs have higher ductility and tensile strength than other techniques, they may have lesser fatigue strength [149].

Advances in solid-state processes

Because they can satisfy a variety of needs for high-performance materials, MMCs find widespread use across many different industries. Choosing the correct reinforcement supplies and manufacturing procedures is crucial for MMCs to achieve their intended qualities. Powder metalworking is the method of choice for solid-state fabrication of MMCs. The improved microstructure and material characteristics made possible by this procedure over more conventional approaches have contributed to its meteoric rise in popularity. Modern powder metallurgy has allowed for even greater improvements in MMC performance and quality. Improved reinforcing particle distribution is achieved by methods like high-energy ball milling, and quicker and more efficient consolidating is achieved through spark plasma sintering (SPS). Improved mechanical as well as physical attributes in composites are the goal of these techniques. In Table 13, we can see how recent developments in powder metallurgy have improved MMC characteristics.

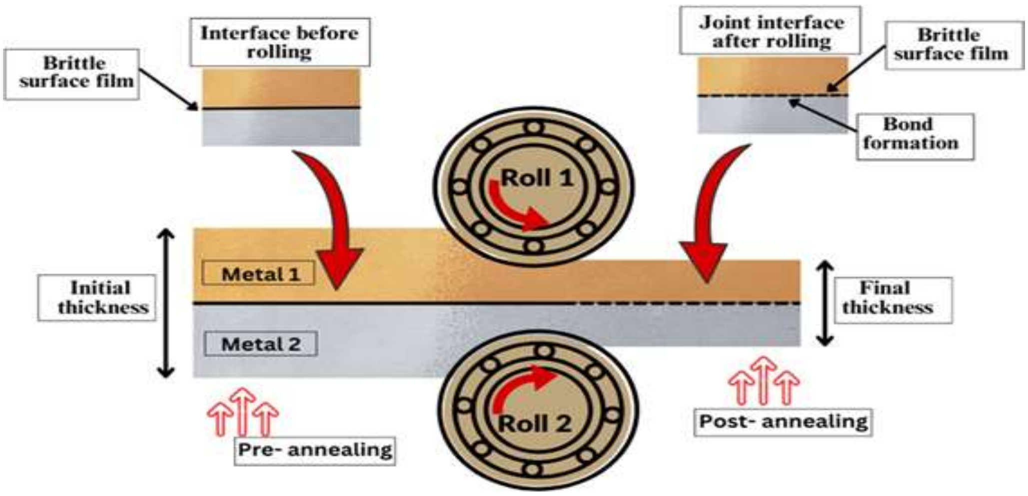

Fig. 12 Deformation process for making laminated MMCs [143]

Modern improvements in solid-state processing allow for the production of MMCs with enhanced strength, durability, and light weight. Applications in the automotive, aerospace, and other high-performance sectors benefit from enhanced methodologies that guarantee higher performance. The possibilities of MMCs in contemporary engineering can be further explored by students and professionals who have a firm grasp of these methods.

Table 13 The advancements in powder metallurgy and their contributions to enhancing MMC properties

Research focus	Key findings	Year	References
High-Energy Ball Milling	Improved reinforcement distribution and microstructural control	2024	[150]
Spark Plasma Sintering (SPS)	Faster and efficient consolidation, resulting in superior mechanical properties and deformation resistance	2018	[151]
Double Pressing-Double Sintering	Enhanced particle dispersion and reduced porosity	2022	[152]
Hybrid Reinforcements (e.g., Graphite, CNT)	Improved wear resistance by up to 88%; peak compressive strength and microhardness achieved at specific	2022	[152, 153]
	reinforcement levels		
Aging and Compaction Parameters	Increased wear resistance and microhardness for Al-nano Al_2O_3 MMCs. Optimal conditions: 550 MPa pressure,	2022	[153]
Ni-Based MMCs	Enhanced tribological characteristics and hardness with ceramic reinforcements	2022	[154]
Hybrid Al_2O_3 + Graphite MMCs	Improved tribological and mechanical properties with optimized ratios of Al_2O_3 and Graphite	2020	[155]
TiO_2 Reinforcements in Al MMCs	Increased compressive strength and hardness with rising TiO_2 content	2021	[156]
Functionally Graded Materials	Superior mechanical characteristics in four-layered structures for braking applications	2018	[157]
Al–Mg-SiC MMCs	Reduced porosity and improved hardness with increased sintering temperature	2019	[158]
Nano ZrO_2 in Al Composites	Improved density, hardness, and particle distribution with prolonged milling	2021	[159]
Copper Matrix Composites	Increased hardness and corrosion resistance with SiC and WC reinforcements	2021	[160]
Al-Based Hybrid Composites	Achieved superior bonding and homogeneous microstructures with SiC and B_4C reinforcements	2023	[161]
Sintering Parameters Optimization	Enhanced density and hardness with increased sintering time for Al/SiC/Al_2O_3 composites	2022	[162]
Cu-B_4C Composites	Improved hardness and density with up to 15 wt.% B_4C reinforcement	2019	[163]

In-situ fabrication of metal matrix composite (MMCs)

There are two primary types of composites that can be made from melt solidification in situ: (1) composites that are a consequence of planned or controlled formation processes [164-166] and (2) composites that are a result of a reaction of chemicals between the melt and solid or gas phases. The second category encompasses phenomena such as exothermic dispersion, a self-propagating high temperature [167–169]. This approach outperforms ex-situ methods in terms of heat stability, binding strength, and reinforcing uniformity.

Very fine and uniformly dispersed reinforcing phases are common in in-situ produced composites. The stable phases have a cohesive interface that aids in strengthening the interaction between the matrix material and the reinforcement. As a result, getting the desired end products requires a firm grasp of reaction kinetics and thermodynamics.

Directed or controlled solidification process

References [164, 165] discuss the possibility of directed or regulated solidification for the in-situ production of composites. Reinforcements, which are structures within the metallic matrix that resemble rods or threads, are formed when one of the phases solidifies by directed or controlled solidification. You can change the spacing of rod or lamellar structures by changing the speeds of cooling or development. A single-phase structure resembling a column can be created from nickel aluminide (Ni3A1) by cooling it at a pace of 25 mm/h; this structure has around 60% tensile suppleness (at ambient temperature). However, for cooling rates more than 50 mm/h, the ductility value of the identical material decreases.

The cooling rate and volumetric percentage of reinforcements decide the separation between rods or lamellae in binary eutectic alloys. Rate of cooling and volume % of reinforcing determine the rod-to-lamellae or solid-to-lamella distance distances in ternary eutectic alloys. The fact that alloying compounds can regulate the reinforcement type is even more remarkable. As an example, TiB rods are formed when alloying elements such as Nb or Ta are added to a TiAl/B melt. However, TiB2 equiaxial nanoparticles are generated when a melting process solidifies in the absence of these additives [166].

Several eutectic systems are included in the fact composites that have been created in situ. As an example, there are materials such as niobium-niobium carbide technological innovation, eutectic superalloys made of nickel or colour cobalt, composites of carbon, iron, and titanium, and rods regarding titanium boride (TiB) created from melts that contain zirconium aluminide (TiAl), boron (B), and antimony (Ta). One disadvantage of directed or controlled solids is their modest development rates, which range from approximately 0.4 to 2.0 inches per hour. The morphological distortions, percentage of volume constraints, and reinforcing form constraints caused by heat gradients have reduced interest in these composites. All of the benefits, drawbacks, and applications of this method are listed in Table 14.

Chemical reaction processing

Chemical reactions between solids, gases, or melting metals can create in-situ composites. This process requires determining possible reactions and conducting a thermodynamic and kinetic study of the driving force. Considerations such as temperature, diffusion techniques across reaction or boundaries layers, gas or solid concentration, and alloy composition dictate these details [170–173]. Al2O3/Al composites generated from aluminium oxidation processes and Al-Cu alloys reinforced with the titanium carbide (TiC) are two examples of synthetic composites produced by chemical methods. Methane (CH4) and argon (Ar) gas are bubbling inside the melt. Titanium diboride (TiB2) reinforced aluminium (Al) alloys produced via exothermic dispersion are another example.

Fast and self-replicating fabrication are two benefits of in-situ procedures that result from extremely exothermic reactions.
The thermodynamic stability of the reaction between products or reinforcement is maintained. There is high interfacial bonding because the reinforcement layer and matrix provide a clean interface. Having said that, in-situ procedures are not without their drawbacks. There is usually a lot of open porosity in the end product—sometimes more than 50%. For high-performance applications, full densification typically requires additional processing steps like infiltration, solid-state consolidation, or hot-consolidation. Table 15 enumerates the numerous benefits, drawbacks, and uses of this method.

Table 14 Advantages, disadvantages, and applications of directed or controlled solidification process

Advantages	Disadvantages	Applications
The process provides better control over the size and distribution of reinforcements It leads to stronger bonding between the matrix and reinforcements The method improves mechanical properties like strength and wear resistance	The process requires expensive equipment for controlled solidification It may not be suitable for large-scale production due to high costs Complex solidification conditions can lead to defects like porosity	Used for making lightweight, high-strength components such as turbine blades and structural parts, and heat-resistant components for missiles

Table 15 Advantages, disadvantages, and applications of chemical reaction processing

Advantages Disadvantages Applications

The method ensures clean and strong interfaces between the matrix and reinforcements
It allows for the synthesis of reinforcements with tailored properties
The process can be used to produce composites with high-temperature stability

Uncontrolled reactions can lead to uneven distribution of reinforcements
The process may require expensive reactants or high-energy inputs
It is challenging to scale up for industrial applications

Used for components requiring excellent thermal and electrical conductivity, such as heat sinks, electronic packaging, and parts for gas turbines and nuclear reactors, where high thermal stability is needed

XI. METAL MATRIX COMPOSITES (MMCS)-FROM SCIENCE TO TECHNOLOGICAL SIGNIFICANCE

So far, the majority of MMC research has focused on lightweight metals such as aluminium (Al), magnesium, also called Mg, and titanium (Ti) for applications in aerospace, automotive, and military structures. These materials are used in aircraft fins, the antenna guiding systems, struts, and drive shafts, as well as brake discs, callipers, and brake discs. On the other hand, materials such as iron, tin, and copper have a lot of promise for tooling and electrical uses.

Automotive components (drive shaft, brake disks and calipers)

Motors, driveshafts, and brake components are just a few of the many transportation-related uses that have propelled MMCs to the forefront of customer preference. For example, modern Porsche sports cars feature carbon fibre composite rotor components that have better thermal insulation and specific heat [174, 175]. To reduce weight and improve wear resistance, the cylinder liner of the Honda Prelude uses aluminum-silicon (Al-Si) matrix composites with 50% boron (B) and carbon (C) [145]. In addition, the piston rings of certain Toyota models are made of aluminium (Al) composites with short fibre reinforcement. Rods for connecting and drive shafts in racing cars are structurally lightweighted using aluminium (Al)-matrix composites reinforced with silicon carbide (SiC) or titanium carbide (B4C) particles. The brake cylinders for the German high-performance train, supplied by Duralcan, are made of aluminium (AlSi7Mg) composite alongside silicon crystalline carbide (SiC) particles bonded together for the element boron weight savings of 43% [176, 177].

Aerospace structures

The low CTE as well as elevated modulus of aluminium (Al) MMCs make them a better choice than highly machined titanium for usage in aeronautical structures. Because of its low density, controlled expansion due to heat, high stiffness, and excellent wear resistance for engines, MMCs find widespread use in the aerospace industry.

They also possess a high specific strength. One example is the substitution of SiC particle-reinforced MMCs for aluminium access points in F-16 aircraft, which increases fatigue life [178]. The F-16's F119 engine uses SiC-reinforced Ti-composites in place of the larger IN718 and stainless-steel components [179, 180]. Other instances include the fan-exit controlling control vane of a Pratt and Whitney is powerplant mounted on a Boeing 777 along with the B20% lighter airframe, primarily made of carbon fibre composites, of a Boeing 787 [181].

Tracksuits for military tanks

The military vehicle industry has aluminium MMC track shoes. Weight savings of up to 25% are possible with the use of SiC whiskers as reinforcement, in comparison to the present-day steel track shoes that weigh more than three tonnes each set. Shoe bushings can have their lifespan increased by a factor of up to 200 thanks to the improved heat dissipation caused by aluminium MMCs.

Electronic substrates

In electronic applications, MMCs are used to address issues related to heat management and thermal decomposition in high-tech integrated circuits. For extremely powerful, high-density multi-chip modules, microelectronics uses a substrate formed of an alloy containing diamond particles in a metallic copper and silver (Cu-Ag) alloy matrix. It has a high thermal conductivity and a thermal expansion coefficient that can be adjusted [182, 183]. Al2O3 carbon-reinforced MMCs with tunable CTE are also utilised in power transmission [184].

Parts of an explosion engine

Their structural integrity and resilience to thermal shock have made MMCs a hot topic in engine research. Components for explosive engines can benefit from the increased refractoriness of ceramic-reinforced titanium-based alloys. In their study on ceramic matrix composites and their high-temperature properties, Liu and Li [185] delve into the application of these materials in harsh conditions.

Satellite in space

Space satellites frequently employ titanium-based and aluminium MMCs because of their impressive strength-to-weight ratio. These materials are commonly used for spacecraft because they are lightweight and give structural integrity [186]. Titanium Metal Matrix Ceramics for Aerospace Applications, written by Singerman et al. [187], explains how spacecraft and satellites can benefit from MMCs because of their strength and low density.

Fins of a fighter-jet aircraft

Fighter jet aircraft, particularly those constructed from magnesium (Mg) or aluminium (Al) and featuring MMCs in their fins, are another example. Thanks to their unique blend of low weight, high specific stiffness, enhanced fatigue resistance, and superior thermal and electrical conductivity, these materials are truly unique. In addition, their CTE is less than average. They are perfect for the rigorous performance standards of military aircraft because of these qualities. Lee et al. [188] analyses a metal matrix nanocomposite (MMC) applied armour system and talks about how MMCs help fighter aircraft parts last longer and work better.

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Sports sector

Sports equipment like carbon fibre and aluminum/titanium matrix composite bicycle frames, squash and tennis rackets, golf clubs, and fishing poles are all made with MMCs [189]. When it comes to sporting products, MMCs are great since they are stiff, lightweight, densely packed, and resistant to fatigue. MMCs offer a number of advantages for sporting goods, such as low density, light weight, excellent fatigue resistance, and high stiffness. Sports gear with these qualities lasts longer and performs better [190].

The biomedical sector

Many biological applications make use of MMCs because of their low density, excellent elastic modulus, inexpensive nature, strong corrosion resistance, and great load-bearing capacities [191–193]. Matrix materials that have reinforcements like hydrogen apatite (HA), chitosan (CS), and the oxide of aluminium (Al_2O_3) have been used in biomedical applications. Ti, Mg, Co, Cr, Ni, and Mo are all part of this group of materials, along with stainless steel (SS316L) [194–197]. Carbonaceous nanomaterial-reinforced MMCs have recently been explored as a potential biomaterial with improved properties and applications [198–201]. New developments in MMC technology have sped up the growth of several industries, including those that make surgical instruments, orthopaedic implants, and prosthetic limbs.

XII. RESEARCH GAPS AND FUTURE DIRECTIONS

There are a number of difficulties that have an impact on the physical and mechanical properties of MMCs, and these difficulties are detailed in the article. Choosing the appropriate production technique for the particular application is one of the primary challenges. By fine-tuning the manufacturing process, one can create a superior product with many desirable attributes, such as increased strength, durability, and resistance to wear.

Future study should investigate and assess the performance of alternative matrix materials for MMCs, despite the fact that progress has been achieved.

One of the biggest problems with composites is the occurrence of air gaps. Due to these flaws, the material's mechanical and physical qualities are diminished [202]. Improving the composite characteristics continuously relies on maintaining a uniform arrangement of reinforcement particles inside the matrix. Disparities in distribution can have a negative effect on the mechanical properties of composites [203].

Enhanced powder metallurgy and ultrasonic stirring are two possible approaches that could resolve this issue. Another important consideration is the wettability of the matrix and reinforcements particles. A decrease in bond strength and overall composite strength can be caused by poor wettability. Composites with improved matrix-reinforcement interaction might be the product of future studies into surface treatments & coating technologies. Sustainability is also rising in significance

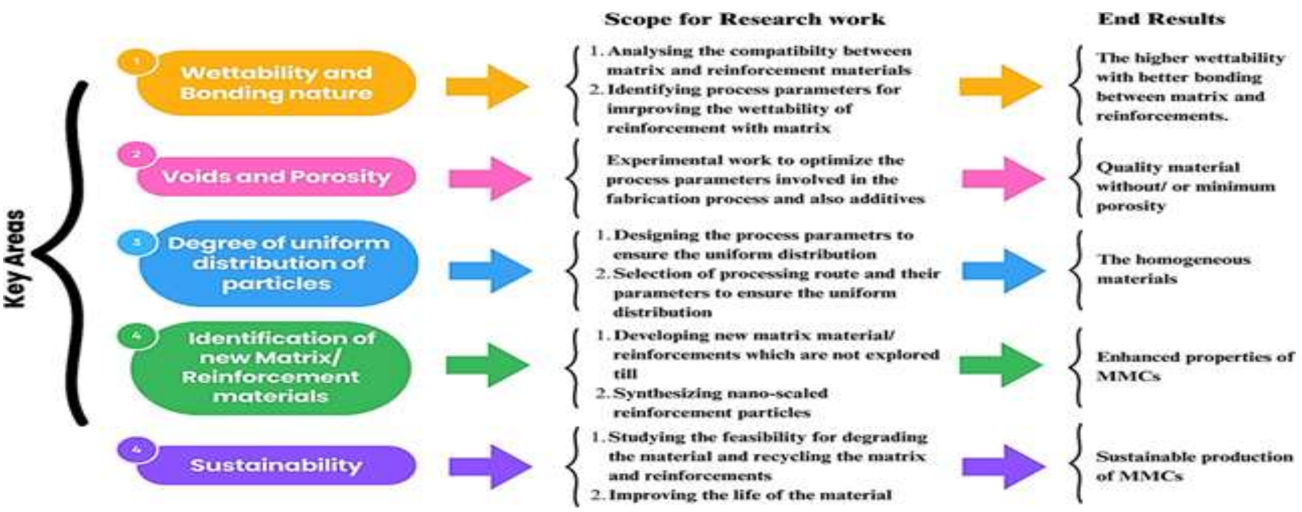

Fig. 13 Future scope and opportunities in metal matrix composites (MMCs)

in regard to MMCs. An increasing number of people are thinking about ways to make these materials more recyclable and creating more environmentally friendly production processes. There has been a global upsurge in interest in environmentally friendly technology. Manufacturers are utilising MMCs to develop lighter and more efficient materials for vehicles and planes that use less fuel. Because of their low weight and great strength, MMCs have recently seen a rise in application in hybrid and electric vehicles. Power transmission cables also make use of these composites due to their high energy efficiency and remarkable mechanical characteristics.
Better production methods, investigation of new materials, and increased sustainability should be the goals of future studies aimed at meeting these issues. Thanks to these developments, MMCs will be able to keep up with the needs of contemporary applications across several sectors [204]. The anticipated results and projected future scope of MMCs are shown in Figure 13.

XIII. CONCLUDING REMARKS

A lot of ground has been covered in the evolution of novel metal matrix composites (MMCs). Using aluminium, copper, magnesium, titanium, and zinc as examples, this article provides a comprehensive overview of the mechanical and physical properties of MMCs. Emphasised are important points drawn from the literature. To reach their full potential, though, a number of obstacles must yet be overcome.
Aluminium (Al): A cheap and lightweight material. Strength, hardness, and resistance to wear are all enhanced by reinforcements such as Al_2O_3, SiC, and B_4C. There has to be more investigation into the problems of vacuum creation and particle distribution.

Copper (Cu): Used for its high thermal and electrical conductivity, it can be reinforced with steel chipping or aluminium oxide to increase its toughness. Improving mechanical characteristics for structural applications requires additional research.

In order to get a high tensile strength, magnesium (Mg) is reinforced with nickel. Ideal for parts with a low profile, but easily corroded. Further investigation into surface treatments and coatings is required.

Improved hardness and compressive strength achieved by reinforcing titanium (Ti) with nanoscale silicon carbide. To prevent a decline in performance, it is crucial to optimise reinforcement levels. Finding the right mix of reinforcement and performance should be the subject of future research.

When combined with alumina particles, zinc (Zn) has the ability to achieve very high strength-to-weight ratios. Optimal mechanical property consistency requires optimisation of the fabrication process.

When it comes to cutting-edge engineering, MMCs are the way to go. It is critical to keep researching and developing new solutions to current problems such void creation during fabrication, uneven particle distribution, and precise parameter selection throughout manufacturing. Future generations of technology and environmentally friendly buildings will likely rely heavily on these materials as they undergo further development.

Data availability No datasets were generated or analysed during the current study.

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