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Research Status and Development of Aluminium Matrix Composite: State of the Art

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Abstract: This review paper encompasses a classification of composite materials, including polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). It discusses the unique properties and fabrication considerations specific to each material class. This article attempts to discuss various methods of fabrication of Composite materials, types of reinforcement available and properties (Physical, Mechanical, and Microstructural) of the composites. The composites with different volume fractions of reinforcement are summarized with respect to property changes. The review highlights the significance of composite material properties, such as strength, stiffness, thermal, and electrical conductivity. It discusses how these properties can be tailored through specific fabrication methods and by incorporating various reinforcements, such as fibres, particles, or additives. A detailed study of the types of matrices and reinforcement is provided so that the best results can be obtained in composite fabrication.

Keywords: Aluminium Matrix Composite; Composite Fabrication; Mechanical properties; Metal Matrix Composites; Physical properties; Reinforcement

1. Introduction

Composite materials are in demand nowadays because of their unmatched set of physical and mechanical properties. Composite is another name for fusion or combination, representing the mixture of two or more different materials. Hybrid is the term used when more than two materials are mixed. Although many reviews on aluminium matrix composites exist, majority of them have focused on either a particular reinforcement, or a single route of manufacture. Nevertheless, systematical investigation of the influence of combinations of reinforcements, particle size, and distribution to the overall AMC performance is still lacking. These parameters are critical parameters of hardness or wear resistance, or tensile properties but have never been synthetically controlled in previous literature. This gap is covered by a current review, which assesses the synergetic impacts of a series of reinforcements and physical properties in the behavior of a composite.The primary purpose of the fabrication of composites is to get higher stiffness, improved endurance strength, a high strength-to-density ratio, and resistance to corrosion and wear[1)].

Composites according to Matrix or Base material can be classified into four categories; these are Metal Matrix Composite (MMC), Polymer Matrix Composite (PMC),

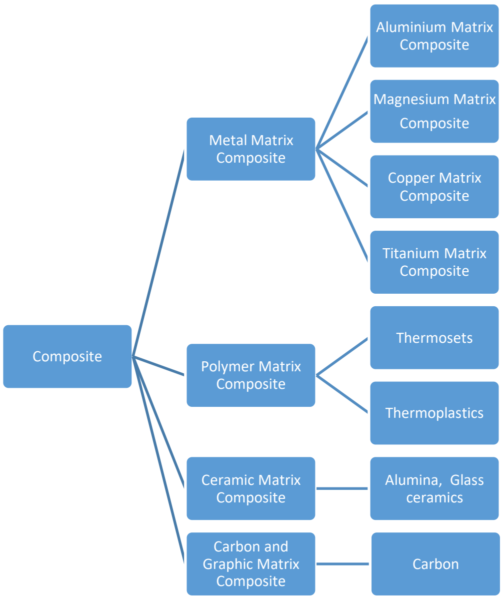

Fig. 1: Classification of composites based on Matrix Type

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Ceramic Matrix Composite (CMC) and Carbon & Graphite Matrix Composites as shown in Figure 1.

A reinforcing material is dispersed into a metal matrix to create metal matrix composites. The reinforcing surface might be coated to stop a chemical reaction with the matrix. Carbon fibres are frequently incorporated into an aluminium matrix to create composite materials with a low density and excellent strength.

Composites primarily consist of a matrix material reinforced with one or more strengthening phases, which work together to improve mechanical and physical properties$^{2)}$.

Matrix: The continuous, monolithic substance embedded in the reinforcement is called the matrix. In contrast to two materials sandwiched together, there is a channel through the matrix to any location in the material. The matrix in structural applications often consists of lighter metals, such as titanium, magnesium, or aluminium, and it offers reinforcement and flexible support. Alloys made of cobalt and cobalt-nickel are frequently used in high-temperature applications$^{3)}$.

***Reinforcement**:* A matrix contains the reinforcing material. The reinforcement can also be employed to alter physical qualities like wear resistance, friction coefficient, or thermal conductivity in addition to its primary purpose of strengthening the composite. Both continuous and discontinuous reinforcement are possible. Discontinuous MMCs can be isotropic and processed using extrusion, forging, or rolling, which are standard metalworking processes. They may also be machined using standard methods, but often, polycrystalline diamond tooling would be required$^{4)}$. Monofilament wires or fibres, such as silicon carbide or carbon fibre, are used for continuous reinforcement. An anisotropic structure is produced, in which the orientation of the material influences its strength, as a result of the fibres being implanted into the matrix in a particular direction. Boron filament was employed as reinforcement in one of the first MMCs. Short fibres or particles called "whiskers" are used in discontinuous reinforcement. Alumina and silicon carbide are the most prevalent reinforcing materials in this classification.$^{5)}$. MMC has wide applications because of its distinctive properties. They have applications in automotive parts because of their corrosion resistance. Other properties that AMC possess includes their sustainability at elevated temperature, resistance to fire, higher conductivity for electrical and thermal applications, and higher strength in terms of stiffness, tensile and compressive strength$^{6)}$.

Moreover, this review presents a holistic source since it uses microstructure analysis methods, bibliometric information to illustrate research trends, and monitors the application of AMC in different industries, including those related to aerospace, automotive sectors, renewable energy, and so on. This has made this work very relevant and of great resource both to the industrial knowledge and the academic world hence making it a reference body to all.

2. Current Knowledge Base

Khan et al. fabricated AMC with Al 7075 as a matrix and particulates of SiC as reinforcements with the powder metallurgy technique. Various microstructure parameters and mechanical properties have been studied in the experimental study. Due to the presence of particulates of reinforcement, hardness, ductility and tensile strength are reduced. Fractography studies reveal that the fracture was a combination of both brittle and ductile nodes$^{7)}$.

Baradeswaran et al. prepared a composite of Al 7075 and B_4C. The stir casting fabrication method was used to prepare a composite. Mechanical properties such as hardness, flexural, tensile and compressive strength were tested. He concluded with the result that with the addition of boron carbide to the matrix, hardness and tensile strength increase, while the Wear rate and coefficient of friction tend to decrease$^{8)}$. Baradeswaran et al., with Elaya Perumal, studied the effect of graphite and alumina on Al 7075 and deduced that wear reduction is achieved. The liquid metallurgy route was used for the fabrication of the composite. With the addition of the ceramic phase, mechanical properties are found to be increased$^{9)}$.

Hindi et al. performed two-stage stir casting to fabricate Al 7075/ grey cast iron composite and study the mechanical properties. Study reveals that hardness and tensile strength increase while ductility decreases$^{10)}$. R. Kumar et al. prepared a hybrid composite of Al 7075 with SiC and graphite as reinforcements through stir casting. Wear tests were performed on the composite and the result is that graphite addition improves the wear resistance of the composite$^{11)}$.

Dasgupta et al. studied the mechanical and wear properties of AMC fabricated through the liquid metallurgy route, taking Al 7075 as the matrix and SiC as the reinforcement. An extensive study reveals that T6 tempering of the composite improves mechanical properties, and the introduction of SiC improves wear resistance$^{12)}$. Senthilvelan et al. fabricated Al 7075 composite with alumina, SiC and B_4C as reinforcements through the stir casting technique followed by hot rolling. Various microstructural and mechanical studies were conducted, including hardness, ductility, UTS and bonding. B_4C as reinforcement has turned out to be the most potent bonding agent and improved mechanical properties$^{13)}$.

Karthigeyan et al. prepared Al 7075 with short basalt fibre using the liquid metallurgy route and studied microstructural properties and mechanical properties. Study reveals increased tensile and yield strength, slight improvement in hardness. Microstructure study shows reduced grain size and homogeneous casting$^{14)}$. Altinkok et al. fabricated a hybrid Al composite with SiC and alumina using the stir casting method. Wear strength is studied and reinforcement results in the decrease in wear strength as wt % of reinforcement increases[15]. Amol Mali et al. use fly ash and alumina to reinforce Al 356 and prepare a hybrid composite with the stir casting. Mechanical properties of the composite are studied, and it is found that up to 12 % addition of reinforcement causes an increase in hardness and ultimate tensile strength, after which it starts decreasing. Compression strength increases, but elongation decreases[16].

Krishnan et al. prepared a composite of AA 7075 with TiC using in situ stir casting. Through various studies, hardness and density were increasing with increasing wt% % of TiC. True axial stresses are highest with 8% TiC and minimum for 0% TiC[17]. H. Abdizadeh et al. produced A 356 Al with ZrO2 using the stir casting method. Results show improved hardness and increased ultimate tensile strength. 15% reinforced in the matrix causes higher ultimate tensile strength casting at 750° C [18]. Boopathi et al. fabricated a hybrid composite of Al 2024 with SiC and fly ash using the stir casting method. Study reveals that density values of Al-SiC, Al-fly ash and Al-SiC-Fly ash composites decreased linearly. Tensile, hardness and yield strength increase by about 57% to the unreinforced Al. Elongation decreases with the addition of reinforcement[19].

Patoliya et al. fabricated Al 6061/ ZrO_2 composite using Stir casting. The study was carried out to explore the mechanical properties of the composite and concluded that Tensile strength, Hardness and Impact strength increase with increases in reinforcement[20]. Koike et al. studied the composite's Microstructure properties prepared through hot powder pressing using Al 5052 /Si_3N_4. The results show that the tendency of melting was found to depend on the grain boundaries, probably because of the observed dependence of segregation on the grain boundary structure[21]. Kumar et al. studied the wear properties of the composites containing SiC, which are superior to those of the matrix, and UTS, density, and hardness increase with the addition of reinforcement. Ductility decreases with an increase in reinforcement. Addition of SiC to the matrix Al 6061 was prepared through the liquid metallurgy route[22].

Baghchesara et al. prepared a hybrid composite of Al-A 356/ $ZrSiO_2$, TiB_2 using Stir casting and studied the mechanical properties of the composite. Up to 10% addition of reinforcement increases the properties i.e. Hardness and tensile strength values, after that it starts decreasing[23]. Kok et al., using the Vortex method, produce a composite material of Al 2024/ Al_2O_3. Various mechanical and microstructural characteristics were studied, which show that Hardness and tensile strength increase with an increase in weight% % and a decrease in size. Density measurement shows porosity, and it increases with an increase in weight %[24]. M. Mabuchi et al. fabricated Al 5052/ Si_3N_{4p} through Powder metallurgy and studied that the maximum elongation is 700% when 20 % reinforcement is added. The melting point is lower than that of a matrix[25]. Mabuchi et al. again used Powder metallurgy to produce composite Al 6061/ Si3N4And studied the microstructural characteristics and superplasticity. The studies shows that grain refinement achieved at 773 K and at a tiny grain size, high-strain-rate superplasticity occurs[26].

Madhusudan et al. prepared a composite of AA-7068/ ZrO_2 using the Stir casting technique and found that Hardness, Tensile and yield strength increase and Elongation decreases with increases in reinforcement[27]. Sharma et al. studied the wear rate of hybrid composite Al 6061/ Si_3N_4, $_n$Gr prepared through stir casting and found that with an increase in reinforcement percentage, the wear rate decreases[28].

Bharath et al. used 3-stage Stir casting to fabricate composite Al 6061/ Al_2O_3 and studied Mechanical and wear properties. Results show that Hardness and tensile strength increase while ductility decreases. Wear rate is less than that of monolithic[29]. Hariharasakthisudhan et al. fabricated hybrid composite Al 6061/ Al_2O_3, Si_3N_4 through Stir casting and concluded that Dual reinforcement performs better tensile strength than single. Compression behaviour and hardness are better due to the presence of alumina than other reinforcements[30]. Kumar et al. fabricated Al 1100/ B_4C, SiC using the Stir casting method and studied wear characteristics. The coefficient of friction is high for aluminium as compared to the composite. Due to the addition of B_4C, wear resistance increases[31]. Zhu et al. studied the microstructure, friction coefficient and wear characteristics of composite Pure Al/ B, ZrO2, Using Powder metallurgy and concluded that the wear rate of the composite increases linearly with the increasing load at elevated temperatures. With the increases in reinforcement, the coefficient of friction decreases. From XRD, it was clear that reinforcement phases were Al_2O_3 and ZrB_2[32].

Kayikci et al. show that the Composite has two distinct zones; one having reinforcement has better hardness and tensile strength, and the other, depleted, has high ductile strength. The sample of composite of Al/ AlB_2 was fabricated through Centrifugal casting[33]. Manna et al. fabricated a hybrid composite of Al 6070/ Al_2O_3, Gr_p using stir casting and performed tests to determine mechanical properties. Results show that Hardness increase with increased volume fraction of reinforcement, and Tensile and impact strength decreases with an increase in reinforcement volume fraction[34]. Philip et al. fabricated a hybrid AA 6061/ TiB2, Al2O3 composite through the Stir casting technique. The authors concluded that the XRD pattern confirmed the formation of TiB_2 and Al_2O3 particulates without any undesirable compounds. Composite experiences brittle fracture at the macroscopic level and ductile failure at the microscopic level. Tensile strength and micro hardness increased with an increase in weight %[35].

Li et al. fabricated a composite of Al as matrix and graphene nanoplatelets as reinforcement using continuous casting and cold pressing and concluded that the fibres of GNP are distributed uniformly and that the phase interface is limited. UTS is 36.8 % higher. Elongation decreases from 11 to 4 %. But the resultant composite is 0.7 % less conducting than pure Al36). Rajesh et al. prepared a hybrid Al 7075/ SiC and alumina composite using the stir casting method. The study observed that hardness increases with an increase in reinforcement and decreases at 15% reinforcement. Wear rate increases with an increase in load37).

Afkham et al. prepare a hybrid composite of Al as matrix and TiO2, ZnO, and Pyrex as reinforcement through in situ stir casting. Microstructure and mechanical characteristics were studied, and the results indicate that Reinforcements with low agglomeration were uniformly present in all matrices. An increase in reinforcement results in an increase in UTS, yield strength, and microhardness, but it also decreases ductility38). Chen et al. fabricated a hybrid Al/ SiC, TiB2 composite using Powder Metallurgy and studied microstructural properties. Microstructure study reveals uniform distribution of SiC and TiB_2 in the matrix. Up to peak value, actual stress increases with true strain39). Das et al. perform stir casting to fabricate Al 7075/ SiC_p. Through microstructural study, uniform dispersion of SiCp particles was revealed, and mechanical properties increase in density and micro hardness, but porosity decreases40).

Dasari et al. perform liquid infiltration and powder metallurgy on the fabrication of Al with Graphene oxide and study various microstructural and mechanical properties. An increase of 28.64% in micro hardness was observed with 0.2 wt% of GO reinforcement. For more improvement in properties, homogeneity is required.41). Guoqiang Huang et al. prepared a composite AA 5083/ WC with Friction stir processing. In microstructural properties, he studied that WC particles were dispersed effectively. Results of mechanical tests reveal that YS and UTS significantly improved, but ductility reduced42). Md Imran et al. prepared a hybrid composite of Al 7075/ graphite, bagasse ash with stir casting and observed improvement in mechanical properties such as hardness and tensile strength compared to the matrix alone43).

Pandey et al. prepared a composite with a stir casting method using Al as matrix and TiC as reinforcement and studied various mechanical properties. Through experimentation, it was observed that hardness and strength increase with an increase in wt% % of TiC. Wear rate decreases with increasing weight% of TiC. Corrosion resistance increases44). Pitchayyapillai et al. fabricated a hybrid composite of Al 6061/ alumina, MoS2 using the Stir casting method and observed that tensile strength and hardness increase with increasing content of alumina but decrease with an increase in MoS_2. Wear and friction resistance of the hybrid composite is superior to that of the alloy45).

James et al. prepared Al 6061/ SiC, TiB_2 hybrid composite using Stir casting and observed that the distribution of TiB_2 and SiC is limited to 2.5 and 10 % in the matrix. Hardness and tensile strength are affected by the addition of TiB_2. TiB_2 improves wear resistance46). Agnihotri et al. fabricated a composite of Al-6061 /SiC using stir casting and observed that Hardness and tensile strength improve with the addition of SiC, wear rate decreases47).

Kumar et al. prepared a hybrid composite of Al 2618/ Si_3N_4, AlN, ZrB_2 through the stir casting method and studied mechanical properties. Results reveal that hardness, tensile and compressive strength increase with increased reinforcement. Wear rate, coefficient of friction, and specific wear rate decrease and wear resistance increases with the addition of reinforcement48).

Dinaharan et al. used friction stir processing to fabricate a composite of AA6061/ RHA (rice husk ash) and studied the homogeneous dispersion of RHA particles in the composite. He concluded that UTS increases with an increase in RHA content49). Hariprasad et al. studied the wear behaviour of a hybrid composite prepared through the stir casting method using Al 5083 as the matrix and B_4C, Al_2O_3 as reinforced material. He observed that wear resistance is improved by increasing % of reinforcement50). Kulkarni et al. prepared a hybrid composite of A356/ fly ash, alumina using stir casting and observed that the developed composite has low ductility and low density. Also, improved compressive strength is noted51). Rebba et al. fabricated a composite of Al-2024/ MoS_2 through the stir casting method and observed that up to 4% addition of reinforcement increases hardness and tensile strength, after which it starts decreasing52). Vedrtnam et al. prepared a hybrid Al/ SiC, Cu composite using the stir casting method. Wear behaviour study shows that the highest % of reinforcement resulted in minimum wear53). Zabihi et al. used the powder metallurgy route to fabricate a composite of Al/ alumina and studied the mechanical properties. The result shows that shear strength and hardness increased, but shear elongation decreased.54). Zhang et al. prepared a composite through hot pressing using Al as a matrix and β-Si3N4 whiskers as reinforcement. Studies reveal that 5% whisker content increases UTS and maintains ductility after this elongation is reduced55).

Research articles about Aluminium Matrix Composites (AMCs) concentrate mainly on established fabrication methods, including powder metallurgy and stir casting. Still, minimal information exists about current techniques like friction stir processing and squeeze casting, along with additive manufacturing. These reviews contribute valuable information about AMCs' mechanical behaviours and tribological traits. Yet, they fail to deliver a consistent analysis of current reinforcement techniques and their combination methods, together with their industrial adoption cases. An exhaustive study of reinforcement type, particle size, and volume fraction and distribution effects on AMCs remains absent in existing reviews focusing primarily on different industrial sectors.

This review fills the existing gaps by delving into current developments for AMC production methods in three main categories: hybrid reinforcements, nano-reinforced composites, and in-situ fabrication processes. This review breaks new ground with its focus on reinforcement synergy because it examines the combined performance effects of different reinforcement materials on strength enhancement, thermal properties, and wear reduction abilities. The review examines how advanced microstructural evaluation methods, which include electron microscopy and X-ray diffraction, help understand material changes. This review provides a complete resource that utilises bibliometric analysis and references vital recent publications to guide researchers and industry professionals who need to optimise AMC properties for automotive, aerospace, and defence applications. The review examines both identified knowledge deficiencies and prospective research pathways because they support the fundamental necessity for this project against present material science developments and manufacturing trends.

3. Manufacturing and forming methods of MMC

MMC fabrication processes depend on matrix and reinforcement selection and their geometry. The basic category for fabrication is according to the physical state of the matrix and reinforcement.

3.1. MMC manufacturing can be of three types- solid, liquid and vapour, as depicted in Figure 2. Sometimes, semi-solid powder manufacturing can also be done for MMC Manufacturing[56].

3.2. Solid State Method

3.2.1. Foil diffusion bonding

Layers of metal foil are sandwiched with long fibres, then pressed through to form a matrix. This is a solid-state fabrication method with a matrix in the form of foils and reinforcement in the form of long fibres. The dispersed phase is by the base, and then pressure is applied at an elevated temperature[57].

3.2.2. Powder Metallurgy

Powdered metal and discontinuous reinforcement are mixed and bonded through compaction, degassing, and thermo-mechanical treatment. Powder metallurgy process may be defined as mixing different metal powders, including matrix and reinforcement, to form finished components after the compression process. The sintering process is done thereafter to achieve the desired properties. The powder metallurgy process comprises the process of powder manufacture, blending of the powder, proper compacting, and sintering.[58].

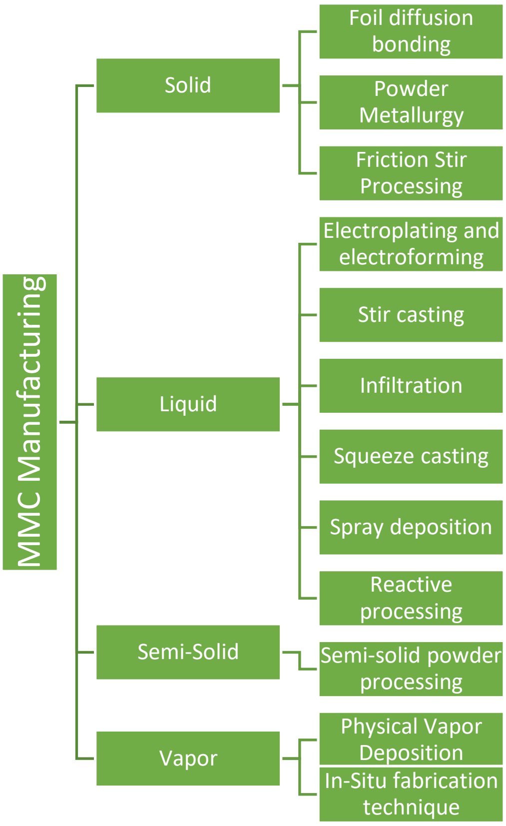

Fig. 2: Classification of Metal Matrix Composite (MMC) Manufacturing Methods

3.2.3. Friction Stir Processing (FSP)

In this process, surface composites are fabricated. FSP is used to produce high-quality solid-state Composites with minimal consumption of energy, good matrix-reinforcement interface, fine composite structure, and without post-processing operations[59]. In addition, the matrix has a uniform distribution of reinforcement particles. This renders the composite material free from porosity and agglomeration and exhibits poor interfacial bonding, making the composite dense and strong enough to withstand loads under various conditions.[60].

3.3. Liquid State Method

3.3.1. Electroplating and electroforming

A solution containing metal ions loaded with reinforcing particles is co-deposited, forming a composite material.[61].

3.3.2. Stir casting

Discontinuous reinforcement is stirred into molten metal, which is allowed to solidify. It is a composite manufacturing technique in which reinforcing materials are mixed with a matrix by a hand-operated stirrer or automatically, and is relatively simple and cheaper. In this setup, the matrix material is heated above its melting point, causing the metal to melt and the impeller to rotate. After the melting of the matrix, the preheated reinforcement is added. After solidification, the composite is ready. This process's significant disadvantage is the uniform distribution of the matrix and reinforcement. To overcome this, sometimes other wettability agents or heat treatment processes are used[62)].

3.3.3. Infiltration

The Liquid Infiltration process involves pressure infiltration, pressureless infiltration and vacuum infiltration process according to the composite to be manufactured. In pressure filtration, the liquid material is pressed at a gas pressure. In vacuum infiltration, the entire process is vented in a vacuum. In Pressureless infiltration, the reinforcement is made porous and is outgassed to the surrounding. Through this method, good finished composites can be fabricated[63)].

3.3.4. Squeeze casting

Molten metal is injected into a form with fibres pre-placed inside it. This process combines the advantages of die-casting and conventional forging technology. Squeeze casting is another name for liquid metal forging, combining casting and forging processes. In this process, the melted matrix and the melted reinforcement are poured into the already preheated die. During solidification, continuous pressure presses the mixture into the die. After the solidification, the extrusion process begins, in which the mould is preheated and filled with another casting[64)].

3.3.5. Spray deposition

Molten metal is sprayed onto a continuous fibre substrate. This method is used to produce metal matrix composites with discontinuous reinforcing materials. This deposition is of great interest in combining matrix and reinforcement when they hold liquid and solid states together. This is achieved by virtually atomising the molten matrix metal with high velocity inert gas jets and simultaneously delivering the reinforcement particulates to the spray zone before they reach the deposition substrate[65)].

3.3.6. Reactive processing

A chemical reaction occurs, with one of the reactants forming the matrix and the other the reinforcement[66)]. By this technique, carbides, borides, or oxides can typically be obtained (e.g. TiB_2, Al_2O_3 or Al_4C_3), depending on the precursor system selected (e.g. Al-TiO_2, Al-B, Al-C). This is normally done by heating the aluminum matrix to 800 to 1000 ºC in which powders or gases emit heat and combine exothermically under supervision. This process provides high matrix -reinforcement bonding, finer microstructures, and does not have the problem of agglomeration as ex-situ methods. There are however some challenges, which include the control of reaction kinetics, and the prevention of brittle structures that are intermetallic such as Al_4C_3 or Al_3Zr. Nevertheless, reactive processing has a future due to the promise it holds in the manufacture of high-performance AMCs in aerospace applications, automotive applications as well as in thermal applications.

The fabrication techniques for aluminium matrix composites (AMCs) are presented in Figure 3 above and are divided into liquid state processing and solid-state processing. The most common processes of Liquid State Processing include Stir Casting, in which reinforcement particles are mechanically stirred into molten aluminium before it is poured into a mould and solidified. Although this is a cheap and straightforward technique, it is prone to porosity, which may impact the final properties of the material[62,67–74)].

Solid State Processing comprises Friction Stir Processing (FSP) and Powder Metallurgy (PM). FSP employs a rotating tool that produces severe plastic deformation,

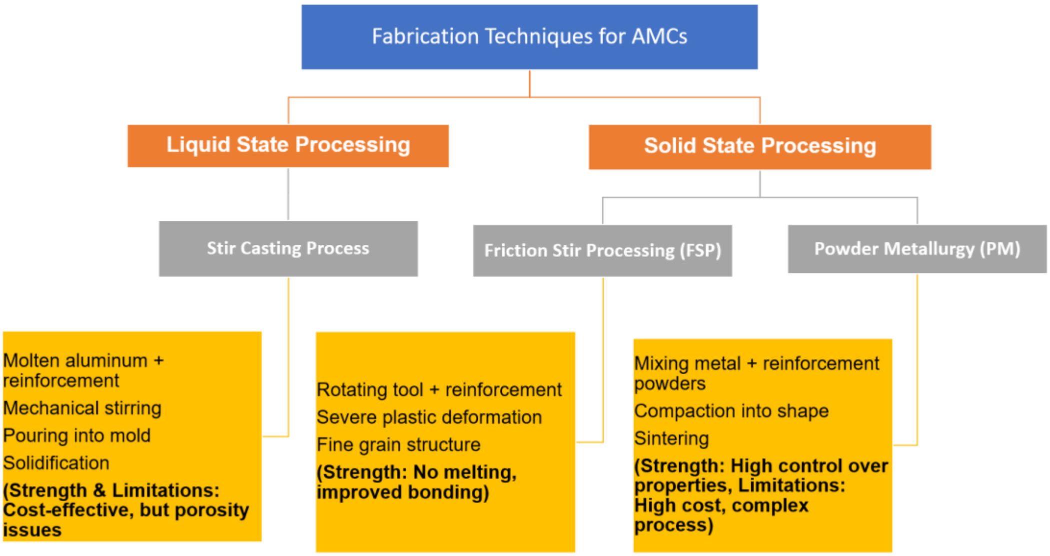

Fig. 3: Fabrication Techniques for Aluminium Matrix Composites

where reinforcements are incorporated into the metal matrix. The primary benefit of FSP is that no melting happens, leading to better bonding of the matrix and reinforcement. Yet it is confined to surface treatments and exceptional use cases. Another Solid-State Processing technique here is Powder Metallurgy, which includes mixing, compacting, and sintering metal powders to achieve the desired structure. Although this technique provides a high degree of control over the properties of the material and the reinforcement distribution is uniform, the manufacturing process is expensive and complex compared with other fabrication techniques 72–78).

3.4. Semi-Solid State Method

3.4.1. Semi-solid powder processing

The semi-solid state method enables the fabrication of advanced composites through heat treatment of metal-powder mixtures until they reach temperatures between the metal matrix's solid and liquid threshold values. The composite enters the next stage when external pressure forms its shape while ensuring that the reinforcement particles remain evenly distributed throughout the matrix79). Fabricating such composites requires aluminium, magnesium or titanium as its primary structural material, followed by reinforcing through SiC, B_4C or Si_3N_4 for improved mechanical properties. A proper mixture of metal matrix and reinforcement powders requires a complete, homogeneous blend as the first step. Heating the mixture ensures a 50-70% solid fraction exists while allowing enough flow for shaping but preventing the matter from totally melting. Pressures from outside sources act through moulds that consolidate the material and create stronger inter-particle bonds while removing excess pores. The controlled cooling process following shaping leads to the composite's solidification while determining the degree of grain refinement and final mechanical characteristics. Powder mixture is heated to a semi-solid state, and pressure is applied to form the composites80).

3.5. Vapour Deposition

Vapour deposition is an advanced manufacturing technique that adds a thin metal or ceramic layer onto substrates, including reinforcing fibers and particles. The process improves mechanical strength and wear resistance properties, thermal properties and reinforcement-to-matrix bonding. Vapour deposition utilises physical and chemical vapour deposition as its fundamental deposition approaches. The comparison of the Physical and Chemical vapour deposition is shown in Table 1.

3.5.1. Physical Vapour Deposition

The fibre is passed through a thick cloud of vaporised metal, coating it81). Physical Vapour Deposition (PVD) is a widely used surface coating technique where the reinforcement fibres or particles are exposed to a vaporised form of coating material in a high-vacuum environment. Common PVD methods include evaporation, where the material is thermally heated until it evaporates and condenses on the fiber; sputtering, where ions from a plasma dislodge atoms from a solid target; and ion plating, which combines evaporation and ion bombardment for dense coatings.

PVD processes typically require a high vacuum environment (10^{-5} to 10^{-7} torr) to minimize contamination and operate within a temperature range of 200ºC to 500ºC, making them suitable for temperature-sensitive substrates. The mechanism involves line-of-sight deposition, where vaporized atoms or molecules travel directly to the fibre or particle surface and condense, forming a thin, dense, and uniform layer82).

In the context of AMC manufacturing, PVD is employed to coat reinforcement materials such as SiC, B4C, or carbon fibres with metals like Al, Ti, or Cr, thereby enhancing wettability and interfacial bonding with the aluminium matrix during subsequent mixing and casting processes. These coatings also improve thermal stability and prevent undesirable chemical reactions at the matrix–reinforcement interface83).

Thus, PVD not only enables improved mechanical performance of the composite but also facilitates compatibility between dissimilar materials, making it a vital step in producing next-generation AMC materials with tailored interfaces.

3.5.2. Chemical Vapour Deposition

The fibre is exposed to reactive gas precursors that undergo thermal decomposition or chemical reactions, forming a solid coating on its surface84).

Table 1: Comparison of Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) in Composite Fabrication

Feature	Physical Vapour Deposition (PVD)	Chemical Vapour Deposition (CVD)
Principle	Involves the physical transfer of vaporised metal atoms onto a substrate85).	Uses chemical reactions of vapour-phase precursors to form a coating86).
Deposition Mechanism	Evaporation, sputtering, or ion plating create a metal vapour cloud that condenses on the fibre surface87).	Reactive gases undergo thermal decomposition or chemical reactions to deposit a solid film88).
Temperature Range	Typically 200–500°C, suitable for temperature-sensitive materials89).	Higher temperatures (600–1200°C) required for chemical

		reactions[90].
Coating Materials	Metals (Al, Ti, Cr, Cu), nitrides (TiN, CrN), and carbides (TiC)[91].	Carbides (SiC, TiC), nitrides (Si_3N_4, TiN), and oxides (Al_2O_3, ZrO_2)[92].
Coating Thickness	Thin films (0.1–5 µm) with high purity and adhesion[93].	Thicker coatings (1–100 µm) with excellent chemical stability[94].
Adhesion Strength	Moderate; may require surface preparation[95].	Stronger adhesion due to chemical bonding[96].
Substrate Coverage	Mostly line-of-sight deposition; limited for complex geometries[97].	Can coat internal surfaces and complex geometries effectively[98].
Process Environment	Requires high vacuum; minimal chemical byproducts[99].	Requires controlled gas flow and byproduct removal[100].

3.5.3. In-Situ fabrication technique

Controlled unidirectional solidification of a eutectic alloy can result in a two-phase microstructure with one of the phases, present in lamellar or fiber form, distributed in the matrix[101]. Figure 4. shows that the methods mentioned above for the fabrication of MMC were used in the past. New technologies like additive manufacturing and advanced in-situ processes have demonstrated the potential to process AMCs with strongly controlled reinforcement structure and few defects in the past years. These methods have many advantages, and they are hardly analyzed in the existing reviews. This paper compiles new evidence on these unrepresented techniques in order to shed more light on the changing fabrication technologies of AMC.

4. Effect of processing parameters on the mechanical behaviour of aluminium matrix composites

The mechanical behaviour of AMCs is affected by various processing parameters such as reinforcement type and volume fraction, particle size, processing temperature, and processing method.

Type and volume fraction of reinforcement: The type of reinforcement used in the AMC affects its mechanical properties. For example, ceramic fibres provide high stiffness and strength, while metal fibres provide high ductility. The volume fraction of reinforcement also affects the mechanical properties of the composite. As the volume fraction of reinforcement increases, the strength and stiffness of the composite increase, but the ductility decreases[102,103].

Particle size: The reinforcement particles' size affects the composite's mechanical properties. Smaller particle sizes can increase the strength of the composite by increasing the interfacial area between the matrix and reinforcement. Still, it can also decrease ductility by introducing more defects into the matrix[104,105].

Processing temperature: The processing temperature of AMCs affects the mechanical properties of the composite. High temperatures can lead to coarsening of the reinforcement particles, which can decrease the strength of the composite. However, high temperatures can also improve the bonding between the matrix and reinforcement, resulting in higher strength and ductility.

Processing method: The processing method used to produce the AMC can also affect its mechanical properties. For example, hot pressing can improve the bonding between the matrix and reinforcement, resulting in higher strength and ductility[106–108]. However, high-temperature processing methods can also introduce defects into the matrix, reducing the ductility of the composite[109].

Mechanical behaviour of AMCs is influenced by various processing parameters as described in Table 2. Therefore, it is essential to optimize the processing conditions to achieve the desired mechanical properties of the composite.

Table 2: Effect of Processing Parameters on Mechanical Behavior of Aluminium Matrix Composites

Processing Parameters	Effect on Mechanical Properties	Remarks
Type of Reinforcement	Ceramic reinforcements (e.g., SiC, B_4C) increase hardness and wear resistance; metallic fibers improve ductility.	Ceramic: Increase strength, decrease ductility; Metallic: Increase ductility, moderate strength[110].
Volume Fraction	Higher volume fraction of reinforcement increases strength and hardness but reduces ductility.	Typically optimized between 10 - 20% for balanced mechanical performance[111].
Particle Size	Finer particles increase interfacial area, enhancing strength, but may reduce ductility and increase porosity.	Nano-scale: increases strength, risk of agglomeration; Micro-scale: balanced properties[112].
Processing Temperature	Higher temperatures improve bonding but can lead to grain growth or unwanted	Moderate temp (~700°C) helps diffusion bonding; very

	phases, reducing overall strength.	high temp cause brittleness[113].
Processing Method	Methods like hot pressing or squeeze casting lead to better bonding and reduced porosity, improving mechanical behavior.	Stir casting is economical; powder metallurgy offers fine control but reduces ductility[114].

5. Effect of Reinforcement on Composite

Table 3 summarizes various studies on the effects of reinforcement on the properties of aluminium matrix composites. It includes information on the matrix material, reinforcement, fabrication process, and parameters tested, such as hardness, tensile strength, wear behavior, and microstructure. The outcomes highlight the impact of different reinforcements (e.g., SiC, Al_2O_3, B_4C, graphite) on mechanical properties, with most studies reporting increased hardness, tensile strength, and wear resistance with reinforcement addition. However, some studies also noted trade-offs, such as decreased ductility or elongation. The processing methods used include stir casting, powder metallurgy, liquid metallurgy, and hot pressing.

Specific findings include increased tensile strength with SiC and Al_2O_3, improved wear behavior with B_4C and TiC, and higher hardness with fly ash and alumina. However, some trade-offs were observed, such as reduced ductility and elongation with increased reinforcement content. The grain structure and fracture behavior varied depending on the type of reinforcement and processing method, with some composites exhibiting improved bonding and microstructural homogeneity. Stir casting was the most common method, along with powder metallurgy and liquid metallurgy for different composites.

Aluminium Matrix Composites have an advantage over single-base metal. According to the application, desired properties can be achieved by adding suitable reinforcement material. Many reinforcements available are Titanium Carbide, Silicon Carbide, Boron Carbide, Aluminium Oxide, Graphite, Silicon Nitride, Zirconium Oxide, Magnesium Oxide, Titanium Oxide, Natural waste material (rice husk, bagasse, coconut shell, bamboo) and Industrial waste material (Red mud, Fly ash), Alumina, Molybdenum Disulphide, Titanium Diboride, Tungsten carbide etc.

6. Properties of MMC

MMC has advantages over monolithic materials in terms of improvements in thermal, physical, mechanical, and tribological properties. Mechanical properties are characterized by stress and strain (tension, compression, shear, torsion), elastic deformation and plastic deformation (yield strength, tensile strength, ductility, toughness, hardness. Physical properties include: appearance, texture, color, odor, melting point, boiling point, density, solubility, polarity, and many others.

6.1. Physical Properties

6.1.1. Density Measurement

Density measurements were made to ascertain the samples' levels of porosity. In cast metal matrix composites, the %age porosity, size, and distribution are key factors in regulating the mechanical properties. To obtain the needed high-performance in-service applications, porosity levels must be kept to a minimum. In composite materials, porosity is primarily caused by air bubbles that enter the slurry during the stirring process or that surround the reinforcing particles[116,117].

Many others have utilised alternate stirring techniques and

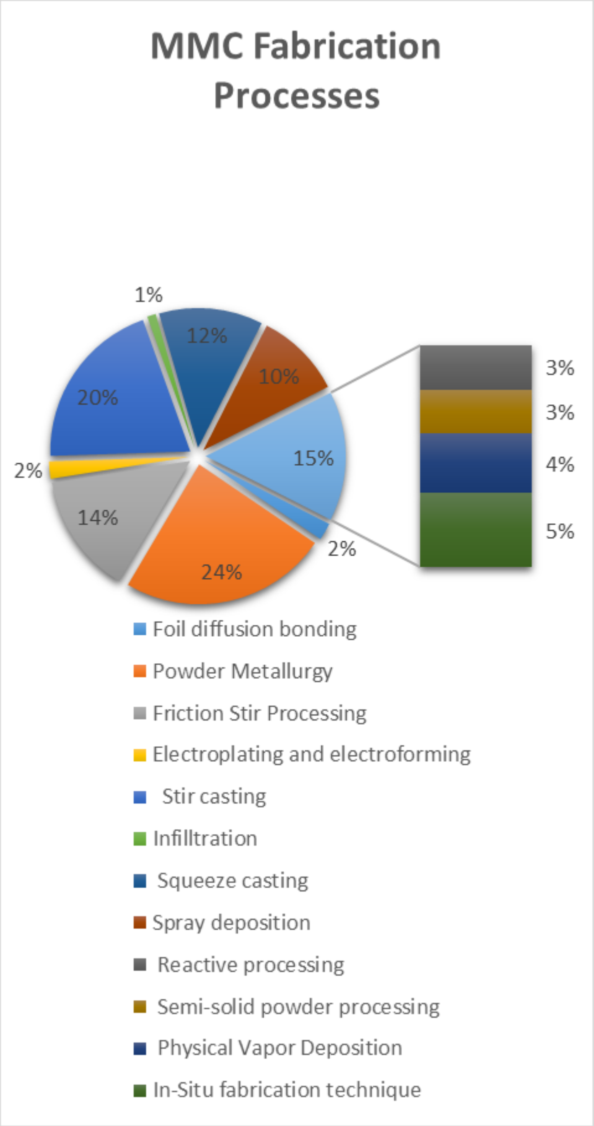

Fig. 4: Overview of Fabrication Processes Utilized in the Development of Metal Matrix Composites (MMCs)

Table 3: Summary of Literature Reporting the Effects of Different Reinforcements and Processing Techniques on the Mechanical Properties of Aluminium Matrix Composites

Investigator	**Matrix/ Reinforcement**	**Process**	**Parameter**	**Outcome**
Ahmed et al.[7)]	Al 7075/ nSiCp	Powder metallurgy	• Grain structure, • Ageing kinetics, • Tensile properties • Fractography	• Ductility and tensile strength reduced. • 30-35% reduced hardness • Coarse grain structure • Fracture was a combination of both brittle and ductile modes.
Baradeswaran et al.[8)]	Al 7075/B$_4$C	Stir Casting	• Hardness test • Flexural test • Tensile test • Compression test • Wear behaviour	• Higher hardness as % of B4C increasing in monolithic alloy. • Increased flexural strength • Increased tensile strength • Increased ultimate compressive strength • Decreased wear rate with increasing % of B4C • Decreased coefficient of friction with% in B4C
Baradeswaran et al.[9)]	Al 7075/ Al$_2$O$_3$, Graphite	Liquid Metallurgy	• Hardness test • Flexural test • Tensile test • Compression test • Wear behaviour •	• Higher hardness as % of Al2O3 increasing in monolithic alloy but decreased with increased content of graphite. • Increased flexural strength • Increased tensile strength • Increased ultimate compressive strength • Decreased wear rate with increasing % of Al2O3 • Decreased coefficient of friction due to presence of graphite.
Zhang et al.[55)]	Al/ β-Si$_3$N$_4$ whisker	Hot pressing	• UTS • Shear elongation	• 5% whisker content increases UTS and maintains ductility after this elongation reduces.
Hindi et al.[10)]	Al 7075/grey cast iron	2 stage stir casting	• Hardness test • Tensile test • Ductile test	• Higher hardness • Improved tensile strength • Ductility decreases as % of reinforcement increases
Kumar et al.[11)]	Al 7075/ SiC , Graphite	Stir casting	• Wear rate	• Due to incorporation of graphite, wear resistance is increased.
Dasgupta et al.[12)]	Al 7075/ SiC	Liquid metallurgy	• Hardness • Wear resistance	• T6 tempering improves hardness and mechanical properties of alloy and composite.

Senthilvelan et al.13)	Al 7075/ $9Al_2O_3$, SiC and B_4C	Stir casting followed by hot rolling	• Hardness • Ductility • Ultimate Tensile strength • Bonding	• Al 7075 with B4C is turned up with strongest bonding and improved properties than the remaining reinforcements.
Karthigeyan14)	Al 7075/ short basalt fiber	Liquid metallurgy	• Microstructure • Hardness • Tensile strength	• Reduced grain size and homogeneous cast • Slightly improved hardness • Improved tensile and yield strength
Altinkok et al.15)	Al_2O_3/ SiC hybrid Al composite	Stir casting	• Wear strength	• Wear strength decreases with increasing content of reinforcement.
Mali et al.115)	Al 356/ fly ash , alumina	Stir casting	• Tensile strength • Ultimate tensile strength • Compressive strength • Ductility • Hardness	• Elongation decreases • UTS increase up to 12 % addition of reinforcement, after that it starts decreasing. • Compression strength increases • Hardness increases with increase in weight % of fly ash and alumina up to 12 % after that it starts decreasing.
Anandkrishnan et al.17)	AA 7075/ TiC	In situ stir casting	• Hardness • Density • True axial stresses	• Hardness and density is found out to be increasing with increasing weight % of TiC. • True axial stresses are highest with 8% TiC and minimum for 0% TiC.
Abdizadeh et al.18)	A356 Al/ ZrO_2	Stir casting	• Hardness • UTS • Fractography	• Increased hardness than unreinforced alloy • Higher ultimate tensile strength is obtained with 15% ZrO2 and casting at 750oC • Failure of composite is same as that of unreinforced alloy.
Boopathi et al.19)	Al 2024/ SiC, flyash	Stir casting	• Density • Tensile and yield strength • Hardness • Elongation	• Density values of Al-SiC, Al-Flyash and Al-SiC-flyash composites decreased linearly. • Tensile and yield strength increases about 57% than the unreinforced Al. • Hardness increases with increases in reinforcement • Elongation decreases with addition of reinforcement.
Patoliya et al.20)	Al 6061/ ZrO2	Stir casting	• Tensile strength • Hardness • Impact strength	• Tensile strength increases with increases in reinforcement • Hardness increases with increases in reinforcement • Impact strength increases with increases in reinforcement

Koike et al.21)	Al 5052 /Si_3N_4	Hot pressing of powder	• Microstructure properties	• The tendency of melting was found to depend on the grain boundaries, probably because of the observed dependence of segregation on the grain boundary structure.
Kumar et al.22)	Al 6061/ SiC	Liquid Metallurgy	• Wear strength • Tensile strength • Ductility • Hardness • Density	• Wear properties of the composites containing SiC are superior to that of matrix. • UTS increase with addition of reinforcement. • Ductility decreases • Hardness increases • Density increases with increase in reinforcement
Baghchesara et al.23)	Al-A 356/ $ZrSiO_2$, TiB_2	Stir casting	• Hardness • Tensile strength	• Hardness and tensile strength values are more than the monolithic material. • Up to 10% addition of reinforcement increases the properties after that it starts decreasing.
Kok et al.24)	Al 2024/ Al_2O_3	Vortex method	• Hardness • Tensile strength • Density • Micro structural characteristics	• Hardness and tensile strength increases with increase in weight % and decreasing size. • Density measurement shows porosity and it increases with increase in weight % • Coarse size of particle I more uniform than finer particles.
Mabuchi et al.25)	Al 5052/ Si_3N_4p	Powder metallurgy	• Elongation • Melting point	• Maximum elongation is 700% when 20 % reinforcement is added. • Melting point is lower than that of matrix.
Mabuchi et al.26)	Al 6061/ Si_3N_4	Powder metallurgy	• Micro structural characteristic • super plasticity	• Grain refinement achieved at 773 K • At very small grain size high strain rate super plasticity occurs.
Madhusudan et al.27)	AA-7068/ ZrO_2	Stir casting	• Hardness • Tensile strength • Elongation	• Tensile and yield strength increases. • Hardness increases with increases in reinforcement • Elongation decreases with addition of reinforcement.
Sharma et al.28)	Al 6061/ Si_3N_4, nGr	Stir casting	• Wear rate	• With increase in reinforcement % wear rate decreases
V. Bharath et al.29)	Al 6061/ Al2O3	3 stage Stir casting	• Mechanical and wear properties	• Hardness and tensile strength increases while ductility decreases. • Wear rate is less as compared to monolithic.

P. Hariharasakthisudhan et al.[30)]	Al 6061/ Al_2O_3, Si_3N_4	Stir casting	• Tensile • Hardness • Compression	• Dual reinforcement performs better tensile strength than single. • Compression behavior and hardness is better due to presence of alumina than other reinforcements.
Uthayakumar et al.[31)]	Al 1100/ B_4C, SiC	Stir casting	• Wear resistance and coefficient of friction	• Due to addition of B4C, wear resistance increases. • Coefficient of friction is high for aluminum s compared to composite.
Zhu et al.[32)]	Pure Al/ B, ZrO_2	Powder metallurgy	• Microstructure • Friction coefficient • Wear characteristics	• Wear rate of the composite increases linearly with the increasing load at elevated temperatures. • With the increases in reinforcement, coefficient of friction decreases. • From XRD it is clear that reinforcement phases were Al2O3 and ZrB2
Kayikci et al.[33)]	Al/ AlB_2	Centrifugal casting	• Hardness • Tensile strength	• Composite is having two distinct zones; one having reinforcement is having better hardness and tensile strength and other depleted is having high ductile strength.
Manna et al.[34)]	Al 6070/ Al_2O_3, Grp	Stir casting	• Hardness • Tensile strength • Impact strength	• Hardness increase with increase volume fraction of reinforcement. • Tensile and impact strength decreases with increase in reinforcement volume fraction.
Philip et al.[35)]	AA 6061 / TiB_2, Al_2O_3	Stir casting	• Mechanical properties • XRD analysis • Fracture	• Tensile strength and micro hardness increased with increase in weight %. • XRD pattern confirmed the formation of TiB2 and Al2O3 particulates without any undesirable compounds. • Composite experienced brittle fracture at macroscopic level and ductile failure at microscopic level.
Li et al.[36)]	Al/ Graphene nanoplatelets	Continuous casting and cold pressing	• Microstructure • Strength • conductivity	• Fibers of GNP distributed uniformly and phase interface is limited. • UTS is 36.8 % higher. Elongation decreases from 11 to 4 %. • 0.7 % less conducting than pure Al.
Rajesh et al.[37)]	Al 7075/ SiC and alumina	Stir casting	• Hardness • Wear test	• Hardness increases with increase in reinforcement and decreases at 15% reinforcement. • Wear rate increases with increase in load.

Afkham et al.[38]	Al/ TiO_2, ZnO & pyrex	In situ stir casting	• Microstructure • UTS • YS • Ductility	• Reinforcements with low agglomeration were uniformly present in al matrix. • Increase in reinforcement results in increase in UTS, YS and micro hardness but decreased ductility.
Chen et al.[39]	Al/ SiC,TiB_2	Powder Metallurgy	• Microstructure • True stress	• Microstructure study reveals uniform distribution of SiC and TiB2 in matrix. • Up to peak value true stress increases with true strain.
Das et al.[40]	Al 7075/ SiCp	Stir casting	• Density, porosity and micro hardness	• Uniform dispersion of SiCp particles. • Density and micro hardness increased but porosity decreases.
Dasari et al.[41]	Al/ GO	Liquid infiltration and PM	• Microstructure • Mechanical properties	• Homogeneous distribution of GO and more homogeneity is required. • Hardness increases with addition of GO %. High strength and ductility.
Huang et al.[42]	AA 5083/ WC	Friction stir processing	• Microstructure • Micro hardness and tensile test	• WC particles were dispersed effectively. • YS and UTS significantly improved but ductility reduced.
Imran et al.[43]	Al 7075/ graphite, bagasse ash	Stir casting	• Hardness • Tensile strength	• Hardness and tensile strength significantly improved than the matrix alone.
Pandey et al.[44]	Al/ TiC	Stir casting	• Wear rate • Corrosion resistance • Hardness, tensile and compressive strength	• Hardness and strength increases with increase in wt % of TiC. • Wear rate decreases with increasing weight % of TiC. • Corrosion resistance increases.
Pitchayyapillai et al.[45]	Al 6061/ alumina, MoS2	Stir casting	• Wear rate • Tensile strength and hardness	• Tensile strength and hardness increases with increasing content of alumina but decreases with increase in MoS2. • Wear and friction resistance of hybrid composite is superior to the alloy.
James et al.[46]	Al 6061/ SiC ,TiB_2	Stir casting	• Microstructure • Hardness • Tensile strength • Wear test	• Distribution of TiB2 and SiC is limited to 2.5 and 10 % in the matrix. • Hardness and tensile strength is affected with addition of TiB2 • TiB2 improves wear resistance.

Hariprasad et al.[50)]	Al 5083/ B_4C, Al_2O_3	Stir casting	• Wear behavior	• Wear resistance is improved by increasing % of reinforcement.
Kulkarni et al.[51)]	A 356/ fly ash, alumina	Stir casting	• Mechanical properties	• Low Ductility and low density. • Improved compressive strength.
Agnihotri et al.[47)]	Al-6061 /SiC	Stir Casting	• Hardness • Wear test	• Hardness and tensile strength improve with addition of SiC • Wear rate decreases.
Rebba et al.[52)]	Al-2024/ MoS_2	Stir casting	• Hardness • Tensile strength	• Up to 4% addition of reinforcement increases hardness and tensile strength after that it starts decreasing.
Vedrtnam et al.[53)]	Al/ SiC, Cu	Stir casting	• Wear behaviour	• A wear behaviour study shows that the highest reinforcement resulted in minimum wear.
Kumar et al.[48)]	Al 2618/ Si_3N_4, AlN, ZrB_2	Stir casting	• Wear rate • Wear resistance • Mechanical properties	• Hardness, tensile and compressive strength increases with increase in reinforcement. • Wear rate, coefficient of friction and specific wear rate decreasing and wear resistance increases with addition of reinforcement.
Zabihi et al.[54)]	Al/ alumina	Powder metallurgy	• Shear strength • Hardness	• Shear strength and hardness increased. • Shear elongation decreased.
Dinaharan et al.[49)]	AA6061/ RHA	FSP	• Microstructure • Tensile behavior	• Homogeneous dispersion of RHA particles in composite. • UTS increases with increase in RHA content.

reported porosity values that were between 2 and 4 percent, which were considered acceptable levels in cast composites. Due to a reduction in the inner-particle spacing, it was discovered that porosity increased with volume percentage, especially for composites with small particle sizes. In other words, combining the longer particle addition time with a decrease in particle size is necessary to increase the volume percentage of MMCs throughout the production stage. Due to the increased contact surface area, the porosity level increased. The early work also reports it[118,119].

Few also have remarked that Al2024-SiC particle reinforced composites have a higher density for the same volume fraction than Al2024-SiC whisker reinforced composites. The higher density of the ceramic particles can be inferred from the foregoing as the cause of the increase in density. Additionally, they have said that the theoretical and measured densities of these composites are equivalent, which increases the volume percentage of these particles and increases the density of the composites[120].

The higher density of the ceramic particles might also justify the debates above. Additionally, it can be seen from the optical micrographs that the specimens' porosity rises as the volume percentage of the particle reinforcement increases.

6.2. Mechanical Properties

6.2.1. Hardness

Hardness is defined as the resistance to indentation or scratching. Brinell, Rockwell, and Vicker hardness testers are among the several tools used to measure hardness.

Theoretically, the rule of mixture for composites of the form

$$H_c = V_r H_r + V_m H_m \qquad (1)$$

In equation (1) suffixes "c," "r," and "m," respectively, stand for composite, reinforcement, and matrix, while "v," and "H," respectively, stand for volume fraction and hardness, aids in approximating the hardness values.

The hardness of fibre reinforced MMC, whisker reinforced MMC, and particle dispersed MMC are all different types of reinforcements, however low aspect ratio particle reinforcements have a substantial impact on the hardness of the material in which they are dispersed[121].

The findings of many studies on the hardness of Al6063, Al6061, Al7075 and other aluminium alloys reinforced with SiC, B_4C, graphite, and zirconium particles can be summed up as follows:

It can be seen that the hardness of the Al7075-Al_2O_3 composite is higher than that of the composite of Al6061-SiC, and this is due to the fact that the matrix Al7075 and Al_2O_3 possess higher hardness. Higher filler content exhibits higher hardness[122].

Sekhar et al. 2003, explored the hypothesis that the rising ceramic phase of the matrix alloy caused the hardness of the Al2024-SiC composites to increase more or less linearly with the volume percentage of particulates in the alloy matrix[123].

Deuis et al. 1996, concluded that the structure of the composite and adequate interface bonding, in addition to the size of the reinforcement, are also important factors in the increase in hardness of composites containing hard ceramic particles[124]. Particulate reinforcements that give increased hardness include SiC, B4C, Al_2O_3, and aluminide[125,126]. Due to the superior hardness and heat resistance properties of the particles that are scattered in the matrix, these composites also have outstanding heat and wear resistances[127–129].

According to research composites incorporating B4C powder in the 7075 aluminium alloy matrix have steadily greater hardness values, lower flexure strengths, and higher fracture toughness than Al7075 alloy that isn't reinforced[130].

Al6061-10 wt% SiC and 3 wt% boron carbide are the ideal proportions for hybrid composites to achieve high hardness and good toughness. It was also noted that Al6061-SiC-B4C and Al7075-SiC-B4C had higher hardness, and that the hardness of the identified composites rose with increased filler content. Compared to unreinforced alloy, hybrid composites are determined to be 75 to 88BHN and 80 to 94BHN, respectively. Superior mechanical and tribological characteristics can be seen in Al7075-SiC-B_4C[131].

6.2.2. Wear characteristics

Wear is the gradual loss of material due to relative motion between an object's surface and the object or objects it is in touch with. Microcracks or localised plastic deformation are two examples of wear damage. There are four types of wear: corrosive wear, surface fatigue wear, and sticky wear. Wear is the gradual loss of material from the operational surfaces of the mechanically interacting component of a tribo system. It can be quantified as a weight loss or volume loss. Pin-on-Disc, Pin-on-Flat, Pin-on-Cylinder, thrust washers, Pin-into-Bushing, Rectangular Flats on a Rotating Cylinder, and similar test apparatus are frequently used for measuring sliding friction and wear characteristics where sample geometry, applied load, sliding velocity, temperature, and humidity can be controlled[132].

The main tribological factors that affect how well-reinforced Al-MMCs operate in terms of friction and wear are the surface finish and the counterpart, applied normal load, sliding speed/velocity/distance, and the effect of temperature. According to findings, as the applied stress was increased, the specific wear rate of aluminium alloy dropped. In comparison to composites, which have greater strength at higher temperatures, aluminium alloy is more susceptible to thermal softening and recrystallisation. Higher temperatures (above 700°C) have been shown to promote grain coarsening and interfacial degradation in SiC-reinforced AMCs, leading to a 10 -15% reduction in tensile strength[133)]. As a result, with larger loads, the wear rate of the aluminium alloy dramatically increases. Al-alloy is kept out of the wear process when loads are minimal because particles act as load-bearing components[134)].

The wear mechanism is greatly influenced by the sliding speed, and the wear rate of composites is reduced at low sliding speeds. The bonding effect between the reinforced particles and the matrix material may be reduced as a result of the micro thermal softening of the matrix material that can occur at high speeds. All materials have an increase in wear rate and total wear loss with an increase in sliding speed, velocity, or distance. Above a particular temperature that separates the moderate and severe wear transition, the wear volume significantly increases. Since the transition temperature of the composite is higher than that of the unreinforced alloy, the wear volume of the composite is smaller. The transition temperature decreases as the normal pressure rises. The reinforcement's enhanced thermal conductivity helps to increase wear resistance[135)].

The composite pin and counter-face often wear out more quickly with increased load. The wear rate is affected by surface roughness. The rate of wear will increase as the roughness increases. The counter material with a lower hardness affects the wear resistance due to mutual abrasion between the counter material and the wear surface of the specimen since the counter-face hardness is inversely proportional to the wear rate. The composite's wear mechanism influences the counterface's wear. One of the appealing characteristics of MMCs is their superior wear resistance. In various stress ranges, it has been discovered that MMCs reinforced with particulates exhibit wear resistance that is roughly ten times greater than that of unreinforced materials[136)].

The findings of many experiments into the wear rate of Al MMC can be summed up as follows:

The initial sliding distance needed to induce moderate wear reduced with increasing volume %, and the rate of severe wear likewise fell linearly with volume fraction[137)].

The effect of dry sliding friction and wear characteristics of B_4C particle reinforced Al5083 matrix composites with 5-10 wt% was examined. Under the same test conditions, it was found that the wear rate of composite containing 10% B_4C was around 40% lower than that of composite containing only 5% B_4C. This experiment unequivocally shows that the B_4C particles have a considerable impact on improving the wear resistance of these composite materials[138)].

According to (Basavarajappa et al. 2007), the dry sliding wear and friction of MMCs are influenced by the microstructural properties, applied load, sliding speed, and sliding distance. They come to the conclusion that significant wear, silicon carbide particle breaking, and composite seizure occur during dry sliding at higher normal loads (60N). The tribological behaviour of hybrid composites with an aluminium base (Al2219) reinforced by SiC and graphite has also been examined. They looked at the tribological characteristics of hybrid composites made with liquid metallurgy and containing 5, 10, and 15% SiC and 3% Gr. According to the results of the tribological tests, the hybrid composite's wear lowers as SiC content rises. Wear rates for composites are rising as sliding speed and normal load increase[139)].

Kaushik et al. (2016), revealed that heat treatment and the creation of composites by adding 15 weight percent SiC improved the hardness, mechanical, and sliding wear resistance qualities[140)]. According to research by Stojanovic et al., hybrid composites made of A356/10SiC/1Gr have a wear rate that is 3 to 8 times lower than that of the A356 base material. When the typical load is reduced and the sliding speed is increased, the wear rate drops[141)]. Uvaraja, et al., found that the wear rate and coefficient of friction of the hybrid composite sample with Al6061-SiC-B_4C (5 to 10%Wt) decrease with increasing volume percentage[142)].

According to Umanath et al., with Al6061 hybrid composites, the wear rate decreases up to 25% as the volume fraction of SiC and Al_2O_3 reinforcements increases. When compared to the matrix alloy[143)]. The individual composites, the hybrid composites' coefficient of friction and wear rates are lower[144)].

The wear resistance of the Al6061-SiC and Al7075-Al2O3 composites are higher, according to Veereshkumar G.B et al., but the SiC reinforcement greatly improved the wear resistance of the Al6061-SiC composites, which display excellent mechanical and tribological features[145)]. Gopi et al. (2013), noted that the Al6061 hybrid composite's wear resistance significantly increased with the inclusion of zircon and graphite. At 400 rpm, the resistance to wear improved by an average of 35%. At 800 rpm, the resistance to wear improved by an average of 28% to 30%[146)].

6.2.3. Tensile strength

The behaviour of a material under tensioned forces is determined by its tensile characteristics. A fundamental and common engineering test for determining material properties like ultimate tensile strength, yield strength, percent elongation, percent area of decrease, and Young's modulus is the uniaxial tensile test. A conventional tensile specimen with defined specifications is subjected to longitudinal or axial load at a specific extension rate until failure. During the test, the applied tensile load and extension are noted for the purpose of calculating stress and strain. A common test procedure for stress testing metallic materials is ASTM E8[147)].

Over monolithic alloys, particle-reinforced Al-MMCs are often found to have higher elastic modulus, tensile strength, and fatigue strength (Singh et al.)[148)]. The strong interface that distributes and transfers the load from the matrix to the reinforcement is the cause of the composites' increased elastic modulus and strength (Chen et al.)149).

The findings of many experiments regarding the tensile properties of Al MMC can be summed up as follows:

Boopathi et al. (2013), noted that an increase in the reinforcement's area fraction in the matrix led to an improvement in the material's tensile strength, yield strength, and hardness. SiC and fly ash are added to Al2024 alloy, which greatly reduces the hybrid MMCs' percentage rate of elongation19).

The tensile strength of aluminium matrix and composites was shown to be greatly increased by AA6061-B_4C composites from 185 MPa to 215 MPa (Kalaiselvan et al.). This is mostly caused by the reinforcement's load transfer strengthening process. By providing greater resistance to tensile stresses, the inclusion of B4C particles in the matrix causes the matrix alloy to become significantly stronger150).

According to (Gomes et al.), SiC and Al_2O_3 are two of the most popular ceramic materials because of their advantageous ratio of density, hardness, and affordability. The material's elastic elasticity, hardness, strength, and wear resistance all significantly enhance when these reinforcements are coupled with Al-MMCs151).

Alumina and other oxide particles, such as TiO_2, have drawn attention as a reinforcing phase with aluminium alloy, according to research by Ravichandran et al., as it is known to increase hardness, tensile strength, and wear resistance152).

The impact of Al2080 alloy reinforced with silicon carbide (SiC) metal matrix composites was investigated by (Chawla et al.). The elastic modulus, work hardening rate, macroscopic yield, and tensile strengths were found to increase with an increase in volume fraction, although this was accompanied by a decrease in ductility153).

Al5210 alloy reinforced with SiC metal matrix composites with a high volume percentage (50%) and varied particle sizes of 10, 28, 40, and 63 m were examined by (Xiao-dong et al.). The results showed that while the fracture toughness increased with increasing particle size, the bending strength of the SiCp/5210 Al composite with a high volume percentage (50%) decreased154).

SiC particles were found to increase the yield strength and elastic modulus of the Al7XXX base alloy while decreasing the final compressive strength and ductility155).

Onoro et al. investigated that the tensile strength of aluminium 6061 and 7015 matrix alloys without reinforcement decreases with temperature increase during age hardening and that the effect of high-temperature mechanical properties of Al6061 with boron carbide (B_4C) improves mechanical behaviour156).

Increasing the particle size of B_4C particles significantly improves the Al6061 composite's resistance to tensile strength. The particle size of 105 was discovered to have the highest tensile strength of AMCs (176.37 MPa). The composite's increased hardness is what causes the rise in strength157).

Corbin et al. noted that because the reinforcing phase in metal matrix composites is typically significantly stiffer than the matrix, it carries a considerable fraction of stress. Stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles have been suggested as the cause of microplasticity in MMCs, which occurs at relatively low stress158).

Swamy et al. discovered that compared to Al6061-Wc composites, increasing the graphite concentration in the Al6061 matrix results in appreciably higher ductility, UTS, compressive strength, and Young's modulus159).

7. Commercialization and Industrial applications of AMCs

Aluminum matrix composites (AMCs) have been extensively researched and developed over the years due to their unique properties such as high specific strength and stiffness, good wear resistance, and thermal stability. These properties make them attractive for various commercial and industrial applications. The Figure 5 depicts the various Industrial applications of the AMCs.

Automotive industry: AMCs are widely used in the automotive industry to reduce the weight of the vehicle, improve fuel efficiency, and increase the performance and safety of the vehicle. They are used in engine parts, suspension systems, brake rotors, and transmission components160).

Aerospace industry: AMCs are also used in the aerospace industry for their lightweight and high-strength properties. They are used in aircraft structures, engine components, and other critical parts161).

Electronic industry: AMCs are used in the electronic industry for their thermal conductivity and electrical insulation properties. They are used in electronic

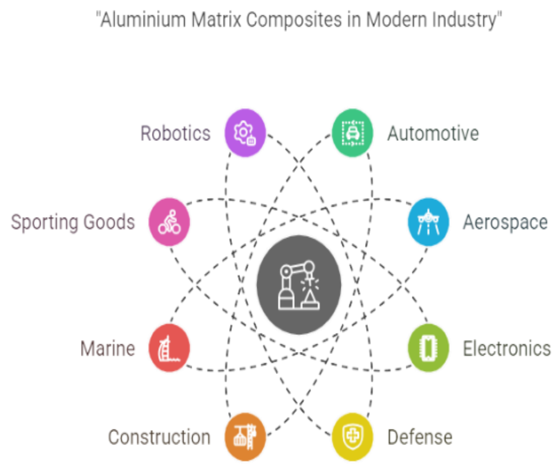

Fig. 5: AMC Applications in the Industries

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packaging, heat sinks, and circuit boards162).

Sporting goods: AMCs are used in the manufacturing of sporting goods such as golf clubs, tennis rackets, and bicycle frames. They provide high strength, stiffness, and durability while reducing the weight of the equipment163).

Military and Defense: AMCs are used in the military and defense industry for their high strength and ballistic resistance properties. They are used in armor plating, bulletproof vests, and other protective equipment164).

Construction industry: AMCs are used in the construction industry for their high strength, stiffness, and corrosion resistance properties. They are used in the manufacturing of building materials such as concrete reinforcement bars and wall panels165).

Table 4: Commercial and Industrial Applications of AMCs with Corresponding Property Requirements and Benefits

Industry Sector	**Application Components**	**Required Properties from AMCs**	**Benefits of Using AMCs**
Automotive 166–169)	Engine blocks, pistons, brake rotors, suspension arms, drive shafts	High strength-to-weight ratio, wear resistance, thermal stability	Improved fuel efficiency, performance, and safety
Aerospace170–174)	Structural panels, wing components, engine parts	Lightweight, high stiffness, fatigue and creep resistance	Weight reduction, fuel economy, extended service life
Electronics175–178)	Heat sinks, substrates, circuit boards, housings	High thermal conductivity, electrical insulation, dimensional stability	Better heat management, miniaturization
Defense & Military179–183)	Armors, vehicle body panels, bulletproof inserts, protective shields	Ballistic resistance, toughness, energy absorption	Protection with reduced weight
Sporting Goods184–187)	Bicycle frames, golf clubs, baseball bats, tennis rackets	High stiffness, impact strength, light weight	Enhanced user performance, reduced fatigue
Construction188–191)	Structural panels, concrete reinforcements, cladding systems	Corrosion resistance, stiffness, machinability	Longevity, reduced maintenance, sustainable design
Railway192–194)	Brake pads, bogie frames, pantographs	High strength, impact and wear resistance	Durability under dynamic loading
Marine195–198)	Hull structures, brackets, engine components	Corrosion resistance, fatigue strength, weight reduction	Improved fuel use and corrosion life
Robotics & Automation 199–202)	Lightweight frames, joints, housing parts	Lightweight, dimensional accuracy, wear resistance	Faster movement, energy savings
Renewable Energy203,204)	Wind turbine arms, solar panel frames	Corrosion resistance, low weight, mechanical strength	Long service life, better energy conversion

AMCs have a wide range of commercial and industrial applications due to their unique properties as depicted in Table 4. As research and development continue, new applications for AMCs are likely to emerge, making them even more versatile and valuable materials.

8. Conclusion and Recommendations

Conclusion: The extensive literature review shown above reveals that although much work has been reported to improve the physical and mechanical properties of various aluminium alloys using multiple types of reinforcements, a synergism in terms of Al6061, Al6063, and Al7075 alloy with Silicon carbide (SiC), Silicon nitride (Si3N4), and Boron carbide (B4C) reinforcements of hybrid composites to improve the physical and mechanical properties by varying weight percentage or particle size has been found. Studies on various forms of reinforcements on hybrid composites have been done worldwide. However, it seems that the combined effect of reinforcement on Al alloy utilising various manufacturing methods has still not received enough attention. In light of the scientific knowledge and practical significance, additional research in this area is required, specifically by altering reinforcement's weight percentage and particle size using low-cost manufacturing stir-casting technology. Another broad topic with plenty of room for research is the behaviour of hybrid composites subjected to solid particle erosion. Studying all the above-mentioned research scopes can aid the research community in gaining excellent knowledge. The originality of the present review may be explained by the combination of bibliometric analysis, the knowledge about tools that help microstructural assessment, and a thorough mapping of AMC applications across various fields of endeavour. This inter- or trans-disciplinary synthesis not only closes any technical gaps, but it maintains a translation of academic work into and out of industrial innovations.

Recommendations: The application prospects of Aluminium Matrix Composites (AMCs) extend to multiple sectors because of their high-performance potential in automotive, aerospace components, defence platforms, and electronic systems. The research achievement of Aluminium Matrix Composites continues toward future advancements with multiple possible improvements.

Normalising fabrication methods that deliver homogeneous particle distribution with minimal material defects is essential. Producing completely defect-free AMCs with improved properties will be possible through the future implementation of friction stir processing, additive manufacturing, squeeze casting, and advanced manufacturing techniques. Integrating artificial intelligence into process controls for optimising methods would result in consistent, scalable outcomes.

Additive manufacturing and in-situ fabrication methods have unique benefits when applied in microstructure control and local reinforcements integration, but they are underused. The further research and reviews should also focus on these newer techniques in order to increase the industrial applicability and optimization of processes.

Research on nano-reinforced, along with hybrid AMCs, exists at a relatively early stage of advancement. These multi-component systems provide ductile properties, along with durability characteristics and toughness. A comprehensive study of these materials' microstructural change, fatigue responses and bonding behaviours between constituents must happen before industrial applications are feasible.

The industrial adoption of AMCs can be sped up by implementing predictive models, digital replicas, and monitoring properties as processes happen in real time. Lowering manufacturing costs by exploring novel reinforcement materials from industrial waste or agricultural by-products will lower AMC's production prices.

The application growth of AMC materials beyond mechanical systems can occur through development in renewable energy domains, biomedical medicine, and high-speed railway fields. Fast adoption of this material requires regulatory backing, industrial partnerships and expertise from multiple scientific fields during material development.

Future research needs to focus on emerging digital production methods, material data handling techniques, and environmentally friendly innovation approaches to fulfil the structural and functional needs of the upcoming generation.

Nomenclature

Al_2O_3	aluminium oxide
B_4C	boron carbide
CMC	ceramic matrix composite
MMC	metal matrix composite,
PMC	Polymer matrix composite
Si_3N_4	silicon nitrate
SiC	silicon carbide
TiB_2	titanium diboride
TiO_2	titanium oxide
ZrO_2	zirconium oxide
$ZrSiO_2$	zirconium silicate

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