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Aluminium metal matrix composites: A retrospective investigation

Girija Moona[a*], R S Walia[b], Vikas Rastogi[b] & Rina Sharma[a]
[a]CSIR-National Physical Laboratory, Dr K S Krishnan Marg, New Delhi 110 012, India
[b]Delhi Technological University, Delhi 110 042, India

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Aluminium matrix composites (AMMCs) are considered to be new generation potential materials for many engineering applications. Different kinds of reinforcement have been infused into the aluminium matrix in order to improve hardness, toughness, stiffness, wear resistance, fatigue properties, electrical properties and thermal stability as compared to their conventional unreinforced counterparts. The characteristics of AMMCs depend largely upon the type of reinforcement materials, interface bonding and processing parameters. In this article we have attempted to investigate the development of aluminium metal matrix composites (AMMCs) along with associated challenges and significant application areas.

Keywords: Metal matrix composites, Discontinues reinforcements, Preform, Hybrid composites

1 Introduction

Metal matrix composites have been able to fulfill all the desired conceptions of the component designers in order to cater the specific demands of different engineering applications[1]. In metal matrix composites, the hard reinforcements are infused into the soft metal matrix to achieve a combination of enhanced physical, mechanical and electrical properties. For development of metal matrix composites, various metals used are titanium, magnesium, copper, nickel and aluminium. But the most widely used base metal is aluminium due to its light weight, strength, excellent thermal and electrical properties, good reflective properties, impermeability and cost effectiveness[2,3]. Aluminium alloys as metal matrix have always attracted material scientists because of some more additional attributes such as better corrosion resistance and high damping capacity. Depending upon the chemical composition of aluminium alloys also, the composites exhibit a variation in their properties for making engineering components executable. Since the automobile, aerospace and sports industries require various aluminium based composites components, to be used in diverse conditions, hence rigorous research has been done in past recent years with different aluminium alloys combined with various reinforcements[4]. Wide applications of AMMC's result into drastic improvement in product design and development with reduced weight, thus offering economically viable alternatives[5]. Main aim of developing metal matrix composites is to achieve desired properties by varying matrix phase, reinforcement shape and size, synthesis route, volume fraction and processing parameters. The available literature shows that adequate investigations have been done to interpret the development mechanism and characteristics analysis depending upon reinforcement content, reinforcement size and process parameters.

By using suitable kind of reinforcement with aluminium matrix, the properties of aluminium metal matrix composite can be altered[6]. In order to estimate the mechanical properties of composites such as density, stiffness and fracture strength etc. following model can be considered[7,8]:

$$P_c = P_m V_m + P_r V_r \quad \ldots (1)$$

For thermal coefficient of expansion the rule of mixtures is as given below:

$$\alpha_c = \frac{\alpha_m V_m K_m + \alpha_r V_r K_r}{V_m K_m + V_r K_r} \quad \ldots (2)$$

where P is property, V is volume fraction and K is thermal conductivity. Subscript c, m and r indicate composite, matrix material and reinforcement, respectively. AMMCs exhibit some phenomenal properties posing tough competition to their monolithic counterparts[9]. Some of the significant mechanical properties of aluminium metal matrix composites properties are discussed below[10].

*Corresponding author (E-mail: moonag@nplindia.org)

(i) Porosity- Porosity plays a very important role in controlling the mechanical properties of the developed composites. Porosity of composites can be expressed as:

$$P_{\mathrm{comp}} = \frac{\rho_{\mathrm{th}} - \rho_{\mathrm{m}}}{\rho_{\mathrm{th}}} \quad \ldots (3)$$

where ρ_{th} and ρ_m are theoretical and measured densities.

(ii) Elasticity- It is of major concern in case of fiber reinforced composites. According to the rule of mixtures in case of composites we have the following expressions:

For axial stiffness:

$$\sigma_c = (1 - V_f)\sigma_m + V_f\sigma_f \quad \ldots (4)$$

$$E_c = (1 - V_f)E_m + V_f E_f \quad \ldots (5)$$

For transversal stiffness:

$$\varepsilon_c = (1 - V_f)\varepsilon_m + V_f\varepsilon_f \quad \ldots (6)$$

$$E_c = \left(\left(\frac{1-V_f}{E_m}\right) + \frac{V_f}{E_f}\right)^{-1} \quad \ldots (7)$$

where σ is stress, *V* is volume fraction, ε is strain, *E* is Young modulus, and subscript *m*, *f*, and *c* describe the matrix material, fiber reinforcement and composite.

(iii) Fracture behavior: Fracture strength is nothing but the stress at which the material fails due to fracture. In composites, if the volume content of fiber reinforcement is higher, the composites fail as the fibers break while if the fiber content is less, then the fibers fail before the base material. The relevant expressions are given below:

$$\sigma_c^{\mathrm{UTS}} = V_f\sigma_f^{\mathrm{UTS}} + (1 - V_f)\sigma_m^{\mathrm{ff}} \quad \ldots (8)$$

$$\sigma_c^{\mathrm{UTS}} = (1 - V_f)\sigma_m^{\mathrm{UTS}} \quad \ldots (9)$$

Many research database show that hybrid composites with uniform reinforcement distribution and reasonable porosity which are more flexible and reliable for various mechanical designs[11,12]. During development of composites, porosity at the metal-reinforcement interface is due to gas entrapment and agglomeration is due to cohesive nature of particles which are the major problems. The distribution of reinforcement materials into metal melt governs the characteristics of composites and the in-service properties of engineering components and it largely depends upon the factors like stirring temperature, stirring time, reinforcement wetting, solidification rate and slurry viscosity, etc. Researchers have also observed that porosity increases with reinforcement addition to the metal matrix, thus for non-wetting conditions, the reinforcement content also has to be optimized. The main reason of porosity is gas entrapment during stirring. When the metal melt is stirred rigorously, air bubbles enter the slurry in many ways. They may be as independent bubbles, air envelope to reinforcement particles, water on reinforcement surface, water vapors from atmosphere and shrinkage during solidification, etc. Due to porosity, the mechanical properties of AMMCs can be affected. The micro pores initiate fatigue cracks under fluctuating load. Ductility of developed composites is reduced, corrosion resistance is increased, tensile strength is reduced and inferior surface finish is obtained[13].

Though during casting, it is not possible to completely avoid porosity yet it should be controlled up to the maximum extent by using inert gas atmosphere during stirring/creating turbulence only at the bottom region of metal melt during stirring/carrying out casting under pressure/closing the pores by extruding the casting, etc. The metal matrix–reinforcement interface, which includes chemical reactions and mutual interactions between preform and metal matrix, is a crucial phenomenon to determine the properties and performance of composites[14,15]. Mixing of those reinforcements which are incompatible with metal matrix can result into less reliable composites with premature failure tendency. In order to enhance interfacial bonding of preform and metal matrix, various surface treatments have been explored[16]. For example, high intensity ultrasonic cavitation effects are incorporated in aluminium matrix to ensure strong interfacial bonding and uniform distribution of reinforcement[17,18]. In addition to this, nanostructures such as nanopores on metal surface, carbon nanotubes and nanofibers, are also introduced into composites for strengthening interfacial bonding[19]. The wettability in metal matrix composites usually depends on three main factors, namely, surface energy of reinforcement, surface tension of liquid metal matrix and interfacial energy between the two.

Increased surface energies of reinforcement, decreased surface tension of liquid metal matrix and decreased solid-liquid interfacial energy are the basic ways to improve wettability. In order to achieve improved wettability various methods are adopted like coating of reinforcement particles, adding alloying elements to the liquid matrix and treating the particles. For example the wettability of SiC particles in aluminium/SiC composites is influenced by factors like free silicon in SiC and wetting angle. To overcome this problem, SiC particles are wrapped in aluminium foil, preheated and then added to aluminium matrix for composite fabrication. Sometimes, in order to enhance the interface bonding between SiC and aluminium matrix, magnesium (<1%) and titanium are added during composite fabrication process[20]. During the analyses of wetting process of aluminium alloy by SiC dip coverage method, some researchers observed that incubation period is decreased by alloying silicon, manganese, iron, chromium, molybdenum, tungsten with aluminium, thus increasing the wettability. Rigorous mechanical stirring and application of external mechanical force to break the gas layer surrounding reinforcement particles can also enhance the wettability.

Filler addition in aluminium composites can be strengthened by using many mechanisms such as hall petch strengthening, orowan strengthening, thermal mismatch strengthening, particle shearing strengthening and load transfer strengthening[21]. In addition to interface phenomena, various reinforcement distribution modals in composites also influence the composite properties[22].

The types of particle size distribution modals of preforms are monomodal, bimodal, trimodal and multimodal distributions. Researchers have worked specifically towards investigation of effect of filler distribution on composite characteristics. Aluminium/SiC particles composites, prepared by pressure less infiltration exhibit linear changes in density with increasing particle size distribution while their mechanical properties such as hardness and fracture toughness show parabolic behavior[23]. Al/Si/SiC composites with multimodal particle size, fabricated by gas pressure infiltration are used for electronic packaging due to their enhanced mechanical characteristics and excellent thermal properties[24]. Aluminium/SiC composites with two different reinforcement sizes and monomodal size distribution show linearly increased thermal conductivity while for bimodal distribution the thermal conductivity first increases with increasing volume fraction and then become constant[25]. Depending upon the reinforcement characteristics, AMMCs can be classified in the following categories (Fig. 1).

1.1 Particle reinforced aluminium metal matrix composites

These composites are developed by reinforcing particle fillers into aluminium metal matrix, through powder metallurgy, stir casting, infiltration and in-situ processing techniques[26]. These are observed to be isotropic in nature and can undergo many forming operations such as forging, rolling and extrusion etc. With particle addition to light metals like aluminum, the hardness, Young's modulus, yield strength, tensile strength and wear resistance increase and thermal expansion coefficient decreases[27].

1.2 Continuous fiber-reinforced aluminium metal matrix composites

The reinforcements are continuous fibers either parallel or braided[26]. Due to high density and the affinity to react with the matrix alloy, the use of metallic fiber usually fails. Since the fibers are infused into the matrix in a certain direction, they form an anisotropic structure, thus exhibit directionality in their mechanical properties such as strength, fatigue, creep and wear behaviour[27,28]. Mainly such AMMCs are developed by squeeze infiltration technique.

1.3 Hybrid aluminium metal matrix composites

These are the composite materials with two or more reinforcements mixed with aluminum matrix, the microstructures of some hybrid aluminium metal matrix composites which are shown in Fig. 2.

Conventional AMMCs show better mechanical properties such as stiffness and strength as compared to unreinforced aluminum alloys, but at the cost of other mechanical properties which are important to prevent premature failure of any mechanical component under in service stress[29]. Hybrid

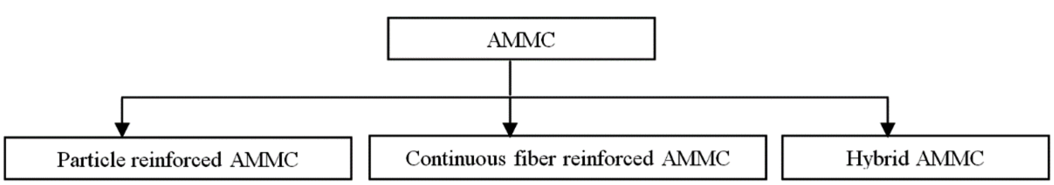

Fig. 1 — Classification of AMMC.

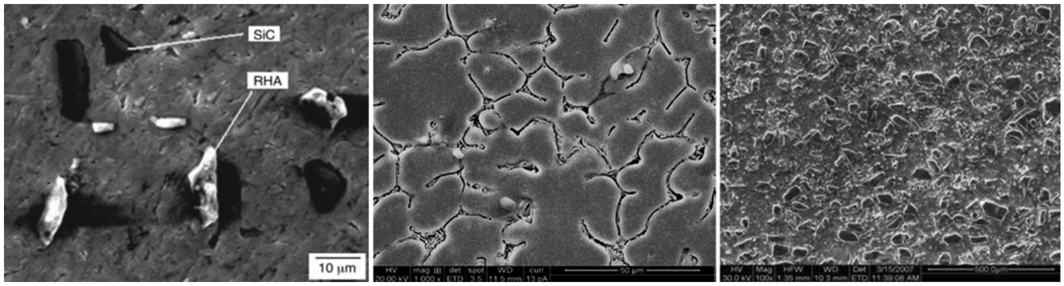

Fig. 2 — Microstructures of hybrid AMMCs.

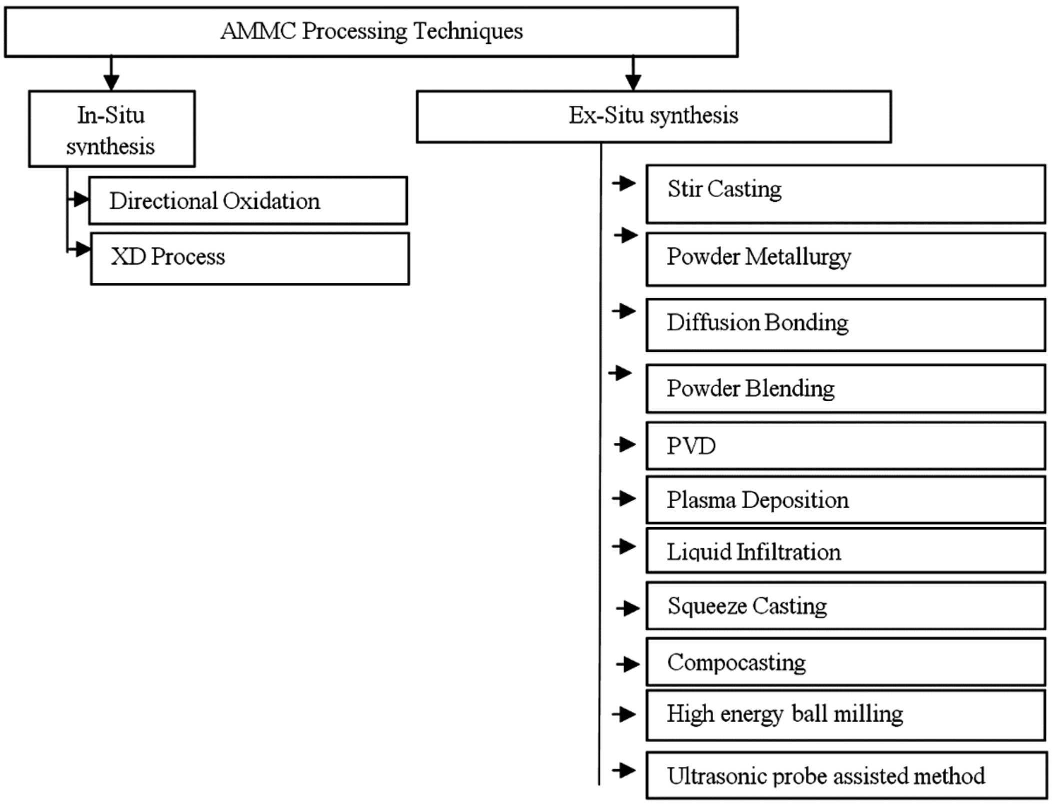

Fig. 3 — AMMC processing techniques.

composites behave in a balanced manner between the advantages and disadvantages of different reinforcements and show improved mechanical properties caused due to reduced interfacial area and reduced meniscus penetration defect[30,31].

2 Processing Techniques of Aluminium Metal Matrix Composites

Aluminium based composites can be developed by using various processing techniques, which are described in Fig. 3. The in-situ synthesis processes involve formation of reinforcements by single step chemical reaction in aluminium matrix, resulting into clean interfaces, better bonding/ wettability and reduced safety hazards. In one of the in-situ processes, when the Al–Mg alloy melts, it infiltrates into the reinforcement and composite is formed. Other process for in-situ synthesis of aluminium composites is known as XD process, where a mixture of ceramics and metallic powders are heated above metal melting point, in order to synthesize the composite[32]. Researchers have also discussed in-situ synthesis of aluminium/Al_2O_3 composite by injecting activated ZnO-Al powder mixture below the melt surface using an injection gun. In this activated powder injection in-situ method, alumina particles of submicron size are formed resulting into almost defect free aluminium composite[33]. A new technique for fabrication of stir cast Al/Ti/Zr/B_4C composite has been proposed and is known as pseudo-in-situ. Here the large B_4C particles are added to aluminium matrix without pre-heating; these particles are subjected to thermal shocks and are converted into fine and contamination free particles with high wettability resulting into uniform distribution[34]. For fabrication of intermetallic reinforced aluminium composites, a new in-situ method was proposed, in which Ni powder was gradually added to molten aluminum by stirring, as a result of which homogeneously dispersed Al_3Ni particles were formed[35]. Controlled gas-liquid reaction methods have also been used for infusion of carbide, boride, and nitride particles into aluminium matrix[36]. There are some limitations for in-situ synthesis techniques. Thermodynamic restrictions and kinetic restrictions limit the composition, nature, shape, size and volume fraction of reinforcement achieved under specified reaction conditions[37]. Some of the ex-situ processing techniques are discussed below.

2.1 Stir casting

This is the simplest and most commercially used technique, and also known as vortex technique. This includes incorporation of particulate reinforcements into liquid aluminium melt and further allowing the mixture to solidify. Here, creating good wetting between the particulate reinforcement and the liquid aluminium alloy melt is very important[38,39]. Properties of composites developed by this method can be altered by varying different process parameters such as pouring temperature, preheat temperature, stirring speed, processing temperature, melt temperature, holding time, size and position of the stirrer, etc.[40].

2.2 Powder metallurgy

As the name powder metallurgy suggests, here fine powdered materials are blended, pressed into a desired shape, and then heated to bond surfaces[41]. Properties of composites, developed by powder metallurgy depend on the characteristics of matrix phase and reinforcements both[42]. Sufficient diffusion must occur during sintering to ensure a uniform microstructure[43]. By following solid state route, one can also avoid solidification defects such as shrinkage and porosity and the reinforcement can be distributed uniformly throughout the metal matrix[44].

2.3 Diffusion bonding

It works on the principle of solid-state diffusion, where the atoms of two solid, metallic surfaces intersperse themselves over time. Here continuous fibers or preforms are sandwiched between foils of the matrix material and then subjected to high pressure on elevated temperature, to establish a bond between the matrix and reinforcement by interdiffusion. To obtain the perfect bonding, the process parameters should be controlled[45,46].

2.4 Powder blending and consolidation

It is a versatile technique for the production of aluminium metal matrix composites. Blending of aluminium alloy powder with ceramic whiskers/particles can be carried out dry or in liquid suspension. Further cold compaction, degassing and high temperature consolidations follow blending[46].

2.5 Physical vapour deposition (PVD)

In this technique fibers are continuously passed through a high partial pressure region of the metal to be used as matrix. On condensation a thick metal coating is produced on the fibers. PVD uses physical process (such as heating or sputtering) to produce a vapour of matrix metal, which is then deposited on the fibre. Further the coated fibers are assembled into an array and consolidated in a hot press[47].

2.6 Low pressure plasma deposition

Aluminium powder plus reinforcement are fed into low pressure plasma. In plasma, the matrix is heated above its melting point and accelerated by fast moving plasma gasses. These droplets are then deposited on a substrate, together with the reinforcement particles[48,49].

2.7 Liquid infiltration

In this technique, the porous body of a reinforcement phase is held and molten aluminium flows through it, filling all the pores and developing a composite. The important process parameters here are initial composition, temperature of reinforcement phase and infiltrating material, nature and magnitude of the external force exerted on the matrix metal and volume fraction of reinforcement[50,51].

2.8 Squeeze casting

Squeeze casting is an attractive processing method for development of porosity and shrinkage cavities free AMMCs with better mechanical properties. This technique is the combination of casting and forging processes that can be done with help of high pressure, applied during melt solidification. The dispersion of reinforcement can be made uniform and bond formation can be improved by controlling their wettability in molten metal by applying high pressure. This process is very fast and provides good surface finish[52].

2.9 Compocasting or rheocasting

In compocasting or rheocasting, the preheated particulates or short fibers are introduced into partially solid and highly viscous slurries of molten metal by vigorous agitation. Thus the reinforcement is entrapped between the proeutectic phase present in the alloy slurry and there is no segregation also. By continuous stirring the slurry becomes less viscous, resulting into mutual interaction between metal matrix and reinforcement, which results into increased wetting and bonding between the two[53].

2.10 High energy ball milling

It is an effective technique to reduce the grain size of the hard phase particulate reinforcement materials and then disperse them uniformly into various base metal matrix including light weight alloys. By optimizing the process parameters and selecting appropriate materials, homogeneous distribution of fine reinforcement can be achieved. Here the mechanical energy is transferred in form of high impact from high energy and high frequency balls to the material being developed. This technique is best suited for development of high density nanostructured metal matrix composite powders with enhanced mechanical properties, which are most appropriate for thermal spray process applications[54,55].

2.11 Ultrasonic probe assisted method

Conventional fabrication methods such as stir casting have many complications in mixing of nano reinforcements into metal matrix due to poor wettability and large surface to volume ratio. Ultrasonic probe assisted method has been proved to be very effective in dispersing nanoparticles in the metal matrix. This system includes ultrasonic probe with a transducer and power source heating furnace, reinforcement addition mechanism, and inert gas atmosphere. Ultrasonic vibrations are used to degas and purify the metal melt and improve the wettability of particle reinforcement. Strong ultrasonic waves create strong cavitation in metal melt, which further creates transient domains for extreme temperature and pressure variations[56]. The nanoparticles clusters are broken by the high temperature and shock force occurred during ultrasonic cavitation and nanoparticle reinforcements are homogeneously distributed in the metal melt to produce composites with enhanced hardness and tensile strength.

Various properties of aluminium metal matrix composites with different reinforcements/ processing techniques are described in Table 1.

3 Applications of Aluminium Metal Matrix Composites

There is huge scope for use of aluminium metal matrix composite due to their superior and tailor made characteristics.

3.1 Aerospace applications

AMMCs have emerged as promising materials having enormous space and avionics scopes, substituting existing aerospace components[108]. Their thermal coefficient of expansion that can be tailored to zero, make AMMCs suitable to avionic applications. The main aerospace parts manufactured using AMMCs are wing slat tracks, bulkheads, doors, landing gear parts, wheels, vertical tails and brakes, etc.[109].

3.2 Automotive applications

AMMCs possess better tribological characteristics, reduced weight, increased component durability, ability to withstand extreme working conditions, higher thermal conductivity, higher damping, self-cleaning and self-healing capability etc.[110]. Light weight automotive parts lead to reduced fuel consumption, reduced emission level and enhanced reliability of the system, thus, meeting the emissions regulations and consumer expectations[111]. Various automotive parts made by AMMCs are pistons and cylinder liners, main bearings, connecting rods, A/C pump bracket, chain covers, alternator/transmission housings, valve covers, intake manifolds, chassis, suspension components and brakes, etc.

3.3 Structural applications

AMMCs are being used to prepare different structural components like walkways, platforms, bridge structures, window frames, door panels, roof structures, large signage, storage containers, marine and offshore structures, power plant structures and handrail components, etc. Aluminium alloys (ductile and tough), mixed with ceramic reinforcements (hard and high in strength) produce composites which are perfectly suitable for structural applications[112]. In addition to these AMMCs possess resistance to extreme environmental conditions, high bearing

Table 1 — Various properties of aluminium metal matrix composites with different reinforcements/processing techniques.

S. No.	Components	Processing technique	Properties
1	$AlSi18CuNi/Al_2O_3p$ (2%)	Stir casting	Increased tensile strength and increased hardness. Better wear resistance[10]
2	AA 6061/SiC/B_4C (0.5-1.5%)	Ultrasonic cavitation based solidification process	Increased hardness, increased tensile strength, slightly reduced ductility, and marginally lower impact energy[30]
3	Al 356/Al_2O_3	Stir casting	Increased hardness[48]
4	Al2219/B_4C/ MoS_2	Liquid metallurgy	Decreased densities, increased micro hardness increases, decreased tensile strength, decreased ductility and better wear resistance[57]
5	Al-Mg-Si/Al_2O_3/Rice husk ash (0-10%)	Stir casting	Decreased density, hardness and tensile strength. Increased specific strength, percent elongation and fracture toughness[58]
6	Al-Mg-Si alloy(6000 series)/SiC/Bamboo leaf ash (0-10%)	Two step stir casting	Reduction in tensile strength and hardness. Increased fracture toughness, improved corrosion resistance and decrease in density[59, 60]
7	Al6061/SiC/Gr (5-15%)	Stir casting	Increased tensile strength and decreased density[61]
8	Al6061/TiO_2/G (3-10%)	Stir casting	Increased hardness and tensile strength[62]
9	Al6061/SiC and Al7075/Al_2O_3 (2-6%)	Liquid metallurgy	Higher tensile strength, improved wear properties, increased hardness and decreased density of composites. Decrease in thermal conductivity, thermal capacity and thermal expansivity in Al6061+SiC composites[63]
10	Al6061-T6/SiC/Gr/ Al_2O_3	Friction stir processing	Decreased micro-hardness, increased wear resistance and better machinability with good surface quality by using EDM, excellent dimensional stability, reduced thermal properties and better wear resistance[64]
11	Al7075/B_4C (5-20%)	Stir casting	Increased hardness and increased wear resistance[65, 66]
12	A356/SiC/Gr	Compocasting	Enhanced tribological properties[67, 68]
13	AA6082/Si_3N_4/Gr	Stir casting	Increased hardness and tensile strength Reduced percentage elongation[69, 70]
14	Al 8090/SiC (5-20%)	Stir casting	Variation in density, porosity and in thermal properties. Increased micro-hardness[71]
15	A356.2/SiC/Rice husk ash (2-8%)	Double stir casting	Increased hardness, increased porosity, increased tensile strength, decreased density and decreased thermal coefficient of expansion[72]
16	Al 8090/SiC/ Calcinated fly ash	Stir casting	Enhanced chemical deterioration in extreme environmental conditions[73]
17	Al 5083/B_4C	Cryomillling and consolidation	Enhanced strength[74]
18	Al6061/Al_2O_3 and Al2124/SiC (6-12%)	Stir casting	Increased hardness, increased tensile strength and enhanced wear properties[74, 75]
19	Al/ ZnO/ CuO	Powder metallurgy	Decreased wear rate[76]
20	Al/Al_2O_3 (20%)	Powder metallurgy	Increased hardness[77]
21	Al/Zn/Al_2O_3	Powder metallurgy	Enhanced thermal stability[78]
22	A6082/ Al_2O_3	Friction stir casting	Increased wear resistance[79]
23	Al 6061/Ni coated Si_3N_4 Particles	Stir casting	Lower wear rate[80]
24	Ak12/Fly ash (9%)	Squeeze casting	Lower porosity and better corrosion resistance[81]
25	Al 6061/Fly ash (10-20%)	Stir casting	Increased tensile strength and hardness and decreased ductility[82]
26	Al6063/$ZrSiO_4$/ Al_2O_3 (0-8%)	Stir casting	Increased hardness and tensile strength[83]
27	Pure Al/TiO_2 (5%)	Stir casting	Improved tensile strength and hardness[84]
28	Al 7075/TiB_2	Stir casting	Increased micro-hardness, increased tensile strength and increased yield strength[85]

(*Contd*.)

Table 1 — Various properties of aluminium metal matrix composites with different reinforcements/processing techniques.

S. No.	Components	Processing technique	Properties
29	Al 2014/TiC (5-10%)	Stir casting	Increased hardness and strength[86]
30	Al 6063/SiC/ Al_2O_3	Stir casting	Increased wear resistance[87]
31	Al 7009/ SiC	Stir casting	Increased hardness[88]
32	LM 25/SiC/Gr	Stir casting	Increased hardness and reduced wear rate[89]
33	Al6063/SiC (3-12%)	Two step stir casting	Improved tensile strength and fracture toughness[90]
34	A 356.1/MgO (1.5-5%)	Stir casting	Increased hardness and compressive strength[91]
35	A359/ Al_2O_3	Electromagnetic stir casting	Increased hardness and tensile strength[92]
36	Al 6061/TiB_2/Gr	Stir casting	Better wear properties[93]
37	Al/Cu (4%)/SiC (5%)	Stir casting	Increased hardness, impact strength and tensile strength[94]
38	Nanostructured composites Al/Al_2O_3	In-situ consolidation during back pressure equal channel angular pressing	Increased compressive strength[95]
39	Al2024/MWCNTs	Cold isostatic press and hot extrusion	High damping capabilities at an elevated temperature without sacrificing the mechanical strength and stiffness of a metal matrix[96]
40	Al 2024/Ag	Powder metallurgy	Increased tensile strength and hardness [97]
41	Al6063/Al_2O_3/Y_2O_3 (0.75-1.5%)	Powder blending and mechanical alloying	Increased micro-hardness[98]
42	Al-Ti-Cr/L12–Al3Ti	Rapid solidification processing	Increased micro-hardness[99]
43	Al/AlN (0-39%)	Arc plasma evaporation followed by consolidation	Improved hardness and elastic modulus of[100]
44	Al-Si7-mg2/SiC (5-15%)	Squeeze casting	Increased tensile strength and hardness and decreased toughness[101]
45	Al7075/Fly ash/ E-glass short fibers	Stir casting	Increased tensile strength, increased hardness and wear resistance[102]
46	AA6063/Al_2O_3/RHA/Gr	Two step stir casting	Increased tensile strength, decreased hardness and enhanced wear resistance[103]
47	Al6063/BLA/SiO_2 (2.5-10%)	Two step stir casting	Improved wear resistance, decreased density and hardness [104]
48	Al-Cu/SiC/Fly ash	Stir casting	Increased hardness, tensile strength, impact strength and improved wear properties[105]
49	Al+TiO_2 (0-12%)	Powder metallurgy	Increased micro-hardness and increased wear resistance[106]
50	LM6+ Al_2O_3 + SiC (0.5-2%)	Stir casting	Increased hardness and tensile strength. Better tribological properties[107]

strength, resistance to out gassing, good wear resistance, good erosion resistance, good thermal conductivity, better dimensional stability, high temperature resistance and high impact resistance, providing better response in the area of structural components[113,114].

3.4 Electronics and communication applications

The prime challenges faced in modern electronic systems are increased power density, ability to withstand extreme operating conditions and high level of integrations[115]. Aluminium metal matrix composites have emerged as good thermal management materials for high reliability applications in power electronics. Al/Gr, Al/SiC and Al/B composites are unmatched packaging materials for high performance thermal management packaging systems due to their lightweight, higher specific strength, better wear resistance, high thermal conductivity and compatible coefficient of thermal expansion[116,117].

3.5 Thermal applications

Monolithic aluminium alloys having high thermal expansion coefficient and poor tribological characteristics, are being replaced by various reinforced aluminium composites for different thermal applications like aerospace and automotive components, semiconductor devices and power electronics components[110]. Al/SiC, Al/Al_2O_3, Al/TiB_2 composites can also be useful for different thermal applications like satellite microwave system, networking, intake-exhaust valves, engine pistons, cylinders, connecting rods, brakes, gears, etc., in automobiles, demonstrating reduced thermal impacts, reduced wear, reduced fatigue at higher temperatures and better dimensional stability with narrow tolerances[118,119].

3.6 Precision applications

Al/B composites are used for making highly precise and dimensionally stable spacecraft structures such as space shuttle mid fuselage main frame, space telescope, antenna and landing gear drag link of the space shuttle orbiter. Al/Gr composites having desired stiffness, excellent electrical conductivity and low coefficient of thermal expansion are used in high gain antenna[120]. Aluminium metal matrix composites like Al/Al_2O_3, $Al/ZrSiO_4$ and Al/fly ash which are developed through powder metallurgy route are used for fabrication of precision parts for automotives. Beryllium reinforced aluminium metal matrix composites, processed through powder metallurgy based semisolid metal forming process , exhibiting high modulus, low density, high thermal conductivity and high heat capacity are used in satellite and avionics precision applications[121]. Many other precision applications of AMMCs are atomic force microscope support frame, robotic arms, video recording heads and advance manufacturing instruments require adequate thermal and load resistance.

3.7 Wear resistant applications

Some recent studies have been conducted to observe the microstructural features, sliding wear behavior, worn surface studies, high stress abrasive wear behavior and subsurface features of Al/SiC composites, projecting AMMCs as potential materials for wear resistant applications. Al/Sic and Al/ Al_2O_3 composites, used for numerous automotive and marine applications, demonstrate superior tribological properties as compared to the unreinforced metal. Al/SiC composites show best wear resistance under dry conditions. Reinforcement of TiB_2 particles into aluminium by liquid aluminium infiltration exhibits increased wear resistance, which may be attributed to the capability of TiB_2 particles to protect the softer metal matrix from abrasion[122]. Due to enhanced wear resistance AMMCs are being used in fabrication of piston, cylinder, brake discs and brake pads leading towards better fuel economy.

Other than these applications AMMCs are also used in sport activity and recreational goods such as tennis rackets, badminton rackets, pole vaults, golf and polo rods and bicycles.

Some of the proven commercial applications of AMMCs areas given below[123]:

(i) Brake rotors made form aluminium composites (AlSi7Mg+SiC particulates) for German high speed train ICE-1 and ICE-2 developed by Knorr Bremse AG.

(ii) The braking systems (discs, drums, calipers or back-plate) of Volkswagen made from particulate reinforced aluminum alloy.

(iii) AMMC continuous fiber reinforced pushrods produced by 3M for racing engines. These pushrods weigh 40% of steel.

(iv) AMMC wires also developed by 3M for the core of an electrical conductor.

(v) Pistons, brake rotors, calipers, liners and propeller shafts manufactured by Duraclan, Martin Mareitta, GKN and Lanxide using Al-SiC particle composites.

(vi) Connecting rods of Nissan using Al-SiC whiskers composites.

(vii) Piston rings of Toyota using $Al\text{-}Al_2O_3$ composite

(viii) Connecting rods of DuPont and Chrysler using $Al\text{-}Al_2O_3$ composite

(ix) Pistons and connecting rods of Martin Mareitta using Al-TiC particle composite.

(x) Engine blocks of Honda using $Al\text{-}Al_2O_3$-carbon fiber hybrid composites.

(xi) Brake rotors of Lotus Elisse, Chrysler and Volkswagen using Al-SiC particle composites.

(xii) Rear brake drum, drive shaft and engine cradle of General Motors using Al-SiC particle composites.

4 Challenges and Future Opportunities

There are several challenges related to the development, commercial viability and wide spread usage of AMMCs. Increased processing cost, lack of theoretically predicted properties, lack of available design data, doubted recyclability, reclamation and secondary processing capability, compromised ductility and toughness are few of the reasons that limit the uses of AMMCs in various sectors in spite of their superior characteristics.

(i) Mechanisms behind different processing techniques is to be understood thoroughly in order to achieve uniform dispersion of reinforcement, strong interfacial bonding and improved wettability without affecting the microstructural integrity of the composites[124]. More emphasis should be given on development of modified processing techniques and controlled process parameters, so that there is no compromise with damage tolerant properties like ductility and fracture toughness, as the infusion of reinforcements into aluminium matrix reduces the ductility making them worse for secondary forming.

(ii) In hybrid composites it becomes very important to understand the role of individual reinforcement component in order to achieve desired properties.

(iii) Performance of AMMCs also depends upon the volume fraction, shape, size and nature of reinforcements, so more work is to be done to produce low cost reinforcements and to develop AMMCs from nonstandard low cost aluminium alloys with desired mechanical, thermal, electrical, tribological and corrosion properties in extreme working conditions[125].

(iv) The corrosion behavior of AMMCs is a strong criterion for selection of aluminium alloys and reinforcements, because processing condition of AMMCs can cause rapid corrosion of composite as compared to the monolithic alloy. The main kind of corrosion in AMMCs is galvanic corrosion, which occurs due to the chemical degradation of interfaces and reinforcements. This can be avoided by controlling microstructure of composites, processing parameters and interactions at the interfaces[126].

(v) There is a need to produce nano-reinforcements with lower cost, improved secondary processing techniques and recyclability for development of aluminium based nanocomposites with uniform distribution, preserved nanostructures and restricted grain growth. Some economical non-destructive kits are to be developed to identify defects in AMMCs during production process[127].

(vi) Sufficient attention is to be paid in order to avoid health hazards while dealing with ultrafine nano-reinforcements.

(vii) Often the use of hybrid aluminium composites is limited due to their difficult machinability. The major problems faced and to be overcome are rapid electrode wear, inconsistent material removal rate, difficult to cut intricate geometries, poor surface finish, requirement of large pulse current and low machining rate etc.[128].

(viii) In addition to above challenges, development of aluminium composites using industrial waste and agro waste is on full swing. Disposal of these waste materials such as fly ash, red mud, palm oil fuel ash, palm oil clinker, rice husk, coconut husk and sugarcane bagasse etc. is a threat to environment, thus more focus should be on recycling them and using them for development of environmental friendly and cost effective composites to be used in various engineering applications[129].

(ix) Various manufacturing technologies for composites to maintain the reliability, durability and machinability of components such as filament winding, pultrusion, sandwich paneling, forming, rolling and 3D weaving etc. are to be developed further[130].

(x) Cast composites usually do not hold well when processed further. So the processing techniques need to be sub-classified in accordance with the production factors, microstructures and applications of AMMCs.

5 Conclusions

Aluminium composites are termed as advanced materials due to their enhanced mechanical, electrical, thermal properties and cost effectiveness as compared to other engineering materials. After going through several research papers related to AMMCs, it can be inferred that the main thing to be considered during fabrication is the end use of developed material. Various factors like processing route, process parameters, base metal and type of reinforcements should be chosen according to the ultimate utilization of fabricated AMMC. Although they have been used in commercial and defence applications, however more opportunities are yet to be explored. Lack of knowledge about possible applications, suitable processing techniques and cost of nano-reinforcements limit their usage. In addition to this, it is extremely significant to investigate the engineering potential of AMMCs because of some critical issues such as machinability, difficulty in secondary processing and degradation in mechanical properties during secondary processing. Economical synthesis of aluminium based nanocomposites is need of an hour for making them more popular. Some of the countries are pursuing consortium and networking approach to enhance the applications of aluminium composites in everyday societal use.

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