A CONSEQUENCE OF REINFORCEMENTS IN ALUMINUM-BASED METAL MATRIX COMPOSITES: A LITERATURE REVIEW

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Abstract

In the recent era, Metal Matrix Composites (MMCs) are one of the most vigorously studied topics in material science. Lightweight metals and its alloys create an intense attraction for tailoring new metal matrix composites to overcome conventional limitations like low strength. Aluminum metal matrix composites signify to the high-grade lightweight high-performance aluminum-based MMCs. The reinforcements in aluminum matrix composites could be in the form of particulates, whiskers, and continuous fiber or discontinuous fiber, where weight or volume fraction varies from a few percentages to 60%. Properties of aluminum metal matrix composites can be customized as per the demand of the industry by getting the appropriate combination of the metal matrix, reinforcements, and selective processing route. Nowadays many grads of aluminum matrix composites are fabricated by different routes where in situ route processing is more attractive compared with conventional ex-situ process because it delivers excellent wettability, thermally stability of reinforcements, the bonding strength between reinforcements and matrix, cohesive atomic structure, and fine grain size of reinforcements (specifically nano size). The devoted research work of aluminum matrix composites during the last three-decade generates a wealth of knowledge on the effect of reinforcements vis-à-vis mechanical, chemical, tribological properties of aluminum matrix composites. The acceptance of the aluminum matrix composites as engineering materials depends not only on the performance advantages of the composites, but it also depends upon the cheap, easy, and familiar fabrication technologies for these tailored materials.

Keywords: Reinforcements; MMC (metal matrix composite); in-situ; composites.

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Introduction

All monolithic materials have their limitation to achieving the right combinations of mechanical, tribological, corrosion, magnetic, electric property, but to overcome and the ever-increasing demand of modern technology, composites are most auspicious materials in recent years [1]. Well established most common routes to fabricate composites are casting and powder metallurgy by adding reinforcements (dispersion strengthen mechanism are also very popular for the same) like oxides, carbides, nitrides, and borides [2-4]. A substantial number of research work and improvement of aluminum matrix composites is observed in these years. There are so many techniques have been industrialized and applied to the fabrication of aluminum matrix composites, such as mechanical stir casting, ultrasonic vibration-assisted stir casting, modified stir casting (two-stage), pressure and pressureless infiltration, powder metallurgy, selective laser melting (SLM), accumulative roll bonding (ARB), squeeze casting, hot pressing, spark plasma sintering (SPS), high pressure die casting, etc. Remarkable factors affecting the response of the aluminum matrix composites are the bonding strength of matrix and reinforcement interface, the chemistry, the size, shape, and distribution of reinforcement, and the matrix composition. Ductility of composites is reducing as the weight or volume fraction of the reinforcements increased, and simultaneously strength of composites is increased. Grain refinement is one of the popular ways to improve ductility and strength at ambient temperature. Under this situation, aluminum reinforced with ceramic particulates have significant potential in structural application due to their high specific strength, stiffness, and low density but negotiate the ductility of the composites [5-7]. Particulates are one of the promising reinforcements of materials used for aerospace, transportation, and industrial sectors for fabricating composites [8].

The aim of this paper is to show recent literature trend for the most significant reinforcements in aluminum-based composites: SiC, Al_2O_3, CNT (carbon nanotube), B_4C, Al-Ti, TiC, TiB_2, Graphene (GO and RGO), and Carbon fiber (C_f). Table 1 shows the summarized production techniques and outcomes related to the process for the most studied reinforcements in aluminum-based composites.

Table 1. Critical outcome of different reinforced Al MMCs.

Reinforcements	Manufacturing Process	Significant Outcome
SiC [9-22]	Stir casting, powder metallurgy **(PM)**, selective laser melting **(SLM)**, centrifugal casting, liquid pressing process, vacuum hot pressing process, extrusion, shock wave sintering, mold forming, and pressureless infiltration, vacuum-assisted high pressure die casting.	• The optimum volume fraction is 50-60 vol%. • As reducing particle size *micro to nano* and to increase *volume fraction*, it improves mechanical, tribological property, and flexural strength. Simultaneously reduces corrosion rate and coefficient of thermal expansion. • It improves wettability with fine particle size. • Thermal conductivity improves with annealed samples. • There is a significant decrease in wear rate at 450 ℃ in Al/SiC nanocomposites systems.
Al₂O₃[23-28]	Flake Powder Melt **(FPM)**, Two-step stir casting, Squeeze casting, Selective laser melting **(SLM)**, Gas pressure infiltration, Pressureless infiltration, Freeze casting.	• The optimum volume fraction is 0-30 vol%. • *Flow stress* increases with strain rate and decreases with temperature in the range of 480 – 360 ℃ in Al/Al₂O₃ nanocomposites systems. • As an increasing heating rate (directly putting inside the preheated furnace at 900 ℃), uniform distribution of Al₂O₃ particles are observed.
CNT [29-35]	PM (along with cryogenic- milling), Solution Ball milling, Sandwich technique, Ball milling.	• The optimum volume fraction is 0-2 vol%. • It significantly improves the mechanical property (tensile strength, yield strength, and

		elastic moduli) and decreases electrical conductivity.
B₄C [36-39]	Stir casting, Powder injection, ultrasonic cavitation- assisted casting.	• Optimum weight percentage is 5-20 wt%. • In Al/B₄C/MoS₂ systems, as MoS₂ weight percentage increases, hardness and fracture toughness decreases considerably. • As reducing particle size *micro to nano* composites tensile strength, impact strength, and ductility increased. • It is observed that increasing the temperature coefficient of thermal expansion is also increases.
Al-Ti base particle [40-43]	Stir casting, PM, Hot pressing and Hot extrusion, ultrasonic vibration-assisted casting, squeeze casting, Hot pressure sintering approach.	• Ti-Al-Nb-B (TNM) crystalline particles have a very good bonding with the matrix. • It improves mechanical and tribological properties.
TiC [44, 45]	PM, Hot pressing combines with hot extrusion.	• The optimum volume fraction is 20-30 vol%. • It improves mechanical properties.
TiB₂[46-51]	Stir casting, Mechanical stirring, In situ technique, Cryomilling – spark plasma sintering, and Pressure infiltration.	• Optimum weight percentage is 0-20 wt%. • It improves compressive strength and coefficient of friction. • It also improves the serviceability of composites at a higher temperature.

Graphene (GO and RGO) [52-54]	Spark plasma sintering, High energy ball milling, and Vacuum hot pressing.	- The optimum volume fraction is 0-1 vol%. - Researchers have objected to the study on uniform distribution of graphene and protect graphene structure while synthesizing. - It improves mechanical properties by adding only 0.25 vol% of graphene.
Carbon fiber (C$_f$)[55-57]	Electromagnetic casting method, self-propagating high-temperature synthesis, semi-solid rolling method.	It improves wetting behavior by adding different stabilizer who creates Ni/P, Ni-Al-Zr, Zr-C interlayer, and it is specifically used to improve bending strength of composites in a structural application.

Effect of reinforcements in aluminum-based systems

SiC reinforced aluminum-based metal matrix composites

SiC is one of the lightest and hard ceramic particulates used as reinforcements in the aluminum-based metal matrix composites. *Zakaria et al.* [9] discussed the Al/SiC composite material produced by the powder metallurgy process. They observed significant improvement in corrosion resistance of Al/SiC composite by reducing the size of the SiC particle from micro to nano and increasing the volume fraction in the composite; authors noted that the Al/SiC composite, compared to the pure aluminum, could be exposed at a higher corrosion rate on 50 and 75 ºC in 3.5 wt.% NaCl aqueous solution [9]. In the hybrid composites, two or more reinforcements are added in the metal matrix simultaneously; this improves the wettability of reinforcements and metal matrix. One of the hybrid composites is Al-Mg-Si/SiC + rice-husk hybrid composite (with mixing ratio of rice husk and SiC was 0:1, 1:3, 1:1, 3:1, and 1:0), fabricated by double stir casting process [10]. Here, the authors observed that hybrid composite improved corrosion resistance compares to base alloy in 3.5% NaCl aqueous solution. Al$_4$SiC$_4$+SiC/Al in situ hybrid metal matrix composite could also be fabricated successfully by a selective laser melt (SLM) process [11]. It was observed that improvement in the wettability of reinforcement to the matrix could be reached by adding fine SiC particles (size of particles was 5 µm). The results were improved by 19% in the coefficient of friction, and a 66% reduced wear rate by adding fine SiC particles compare to coarse particles [11]. SiC/Al composites fabricated by the centrifugal casting process were examined in the literature [12]; SiC/Al prepared slurry was poured at 700 ºC in preheated graphite mold at 250 ºC with 700 rpm. Composite slurry caused to lead and to refine primary α (Al) phases, instance segregation of phase and modified eutectic silicon. Due to centrifugal force, SiC

particles and some primary α (Al) phases drifted to the outer region of the castings, resulting in a particle-free zone in the middle zone of the casting sand a macro-segregation along the centrifugal force direction [12]. *Hyungsoo Lee et al.* examined A356/SiC composite fabricated via liquid press method [13]. Under this process, 56 vol.% of SiC was achieved and found the homogeneous distribution of particles; which shows the best combination of strength, strain, and highest dynamic toughness. Because the crack propagation was effectively blocked by the molten aluminum matrix and deformation band formation, while the T6-heat –treated A356/SiC composites not able to show high strength, but it resulted in lowest compressive strain [13]. Densely packed Al/SiC composites and Al used for finite element modeling and analysis of thermal expansion behavior was observed in the paper [14]. Effectiveness of the coefficient of thermal expansion (CTE) of composites was higher with a non-interpenetrating microstructure than that of the composites having interpenetrating microstructure [14]. Al/50 vol.% SiC composites containing different sizes of SiC particles (average size of 23, 38, and 75 µm) prepared by the powder metallurgy method were reported in the literature [15]. Due to coarse SiC particles, high thermal conductivity and coefficient of thermal expansion were achieved, while fine particles were responsible for the decrease in coefficient of thermal expansion and increased the flexural strength of composites. It was found that annealed composites were slightly decreased flexural strength and coefficient of thermal expansion, and thermal conductivity was increased. Thermal conductivity depends on the particle size of reinforcements due to that as size reduces, the thermal conductivity was increased [15].

In recent years, one of the challenging tasks is to distribute CNT (carbon nanotube) in the metal matrix. A novel approach developed to disperse CNT in the matrix where SiC particles were used as "carrier" was presented in the study [16]. It was shown that with the help of the chemical vapor deposition method, CNT was grown on the micro size surface of SiC, forming nano and or micro-sized hybrid composites named Al/SiC (CNT). Three different sizes of SiC particles (13, 7, and 2.5 µm) were selected for fabrication, and remarkable strength was achieved for SiC particle size of 7 µm [16]. Al6082-5%SiC-5% Graphite (Gr) hybrid composite was fabricated by stir casting method (500 ℃ preheated SiC particles were added in the metal matrix and mechanically stirred at 400 rpm for 10 minutes.) [17]. The wear coefficient of hybrid composites was slightly decreased after annealing, and it increases with an increase in load and grit size of SiC and Gr [17]. Al2024-10 vol.%SiC composites can be produced via powder thixoforming [18]. First Al particles and oxides 10 wt.% SiC particles were ball milled, followed by thixoforming at 400 ℃ with punch velocity 60 mm/s and pressure of 160 MPa [18]. The tensile property of the composites was depending upon mold temperature because it influences the recrystallization behavior, plastic deformation during the thixoforming process, secondary solidification structure behavior, and compactness of secondary solidified structure. Improvement in tensile strength was achieved at 350 ℃ of mold, which was observed as an improvement of 235.4% in tensile strength and reduction in ductility of about 31% [18]. $SiC_{nw}/6061Al$ composites fabricated by extrusion was reported [19], where hot extrusion was carried out at 520 ℃ with 10 mm/s ram speed with extrusion ratio was 11:1. Composites showed a significant increase in mechanical property, where the increase in elastic moduli was reported predominantly due to the densification effect. After the extrusion process, the ratio of strengthening efficiency was improved by 0.6 [19]. Al/SiCn-carbon hybrid composite fabricated by mechanical

alloying of composites powder followed by hot pressing was presented in the literature [20]. There were two types of carbon (glass carbon and multiwall carbon nanotube) used for fabrication. In the presence of the carbon, the coefficient of friction stabilizes, only glass carbon composites show better results for wear resistance than the multiwall carbon nanotube. The most considerable alteration in wear test was observed at 450 ℃ with the Al-SiCn-glass carbon composites [20]. Al6061/SiC and A356/SiC composites were fabricated by the vacuum-assisted high-pressure die casting method [21]. The major outcomes of the paper [21] were to achieve a homogenous distribution of SiC particles, to study 3D characteristics of pores, improvement in particles to matrix interface, and to examine mechanical properties of the composites. Compared to the gravity die casting process, a vacuum-assisted high pressure die casting method shows significant improvement [21]. Functionally continuous graded AA7075/SiC composites with 6.5% SiC and 9.5% SiC particles fabricated by the centrifugal casting process [22]. As particle volume fraction increase, the density of the composites decreased due to increment in casting defects. An increase in sliding speed, load, and sliding distance leads to an increase in the wear rate of functionally graded composites, and results showed functionally graded Al/9.5%SiC composites were superior to the cast and other composites [22].

Al_2O_3 reinforced aluminum-based metal matrix composites

The Al_2O_3 is one of the most attractive additives in aluminum matrix composites for improving mechanical properties. In the paper [23], flake powder metallurgy (FPM) was used to fabricate Al/Al_2O_3 nanocomposites via an in situ routes. FPM method produces intergranular Al_2O_3 nanoparticles with a lamellar shape in the aluminum matrix by refining the thickness of the ball-milled aluminum flakes [23]. The compression test was used to study the effect of flow stress by increasing the strain rate; the authors show that Al_2O_3 particles reinforce the aluminum matrix. It was observed [23], form the microstructure evaluation and processing map, that dynamic recrystallization occurred at the 480 ℃ with a strain rate from 0.001 to 0.01 s^{-1}. The optimum hot working condition was at 480 ℃/ 0.001 s^{-1} [23]. In another paper [24], two-step stir casting method was used to fabricate hybrid aluminum composites with alumina, rice husk ash (RHA), and graphite (as cast AA6063 alloy was first melted at 720 ± 30 ℃, after that it was cooled at its semi-solid condition at 600 ℃; preheated alumina, RHA, and graphite was added with mechanical stir at 400 rpm for 10 minutes) [24]. The composites with graphite show low susceptibility of wear compared to composites with alumina and RHA. As graphite content increases from 0.5 to 1.5 wt.% wear resistance decreases [25]. Stir method was used to fabricate hybrid aluminum matrix composites with SiO_2 and Al_2O_3 reinforcement [26]. As the weight percentage of SiO_2 particles increases, the dendrite arm spacing of α-Al grain decreases. As SiO_2 increased liquids temperature decreased [26]. The elastoplastic finite element model was studied for the thermomechanical behavior of aluminum composites reinforced with alumina particles [27]. The FE results have a reasonable correlation with the experimental data, and the effects of microstructural parameters, voids, and properties of the constituents were further discussed. In order to study the influence of voids on the elastoplastic behavior of composites, the Gurson–Tvergaard–Needleman (GTN) model is applied [27]. Indigenously developed stir casting technique was used to fabricate aluminum matrix composites reinforced with zircon tailing sand (comprised of SiO_2 and Al_2SiO_5). Particle dispersion and wettability at

SiO_2/Al interface were improved with the optimized process parameters (i.e., particles preheating at 700 ºC × 1 h, feeding rate at 10 g/min and stirring time for 10min) [28].

CNT (carbon nanotube) reinforced aluminum-based metal matrix composites

A carbon nanotube is a potential reinforcement for improving mechanical and tribological properties where its volume fraction is very nominal compared to other reinforcements (0.1-1 vol.%). *Biao Chen et al.* [29] studied microstructure, mechanical, and conductive properties for Al/CNT composites, fabricated by powder metallurgy. They show a uniform distribution of CNTs in the aluminum matrix within a low content (0.75 vol% CNTs), but as volume fraction increases, agglomeration of CNT occur, reducing tensile properties. Thermal conductivity and electrical conductivity decreased, and yield strength was increased due to grain refine and oxygen-rich interface [29]. The new approach, using solution ball milling, was developed for the fabrication of aluminum matrix composites reinforced with CNT [30]. Under this approach, uniform dispersion of CNT was observed with a large aspect ratio, small damage of CNT and without the unbundling of CNT in aluminum powders [30]. Carbon nanotube reinforced aluminum matrix composites were synthesized using an equal-channel angular extrusion route [31]. The well-densified composites with only 2 vol.% of CNTs exhibit an approximately 30% increase in yield strength compared to the pure aluminum [31, 32]. The load transfer capability of the interface was studied for multi-walled carbon nanotube reinforced in aluminum matrix composites. It was observed that the load transfer capacity and yield strength improved with the presence of the Al_4C_3 as interface developed between reinforced and aluminum matrix with appropriate quantity under precisely controlled heat treatment [33]. A small addition of CNTs via the powder metallurgy route leads to a significant enhancement in stiffness, strength, and elasticity of aluminum matrix composites. Under this strength, enhancement was proportional to CNT diameter and the fracture behavior of Al/CNT composites. It was mainly governed by the size characteristics of CNTs [34]. Al2009 aluminum alloy matrix composites were reinforced with highly dispersive carbon nanotubes (CNTs) prepared via cryogenic milling combined with powder metallurgy [35]. Most CNTs retained tubular structure in composites except only minimal ones reacted with aluminum and formed the Al_4C_3 interface. With the increasing addition of CNTs in composites, dispersity gradually decreased, and limited dispersion was found when CNTs content is 1.5 wt.% [35].

B_4C reinforced aluminum-based metal matrix composites

B_4C is used to enhance the mechanical and tribological properties of the aluminum-based systems. *Yu Li et al.* studied the mechanical and microstructural effects of B_4C and B_4C-Al_3Ti reinforced aluminum composites fabricated via a stir casting technique [36]. They found that a higher amount of Ti in the matrix leads to increase volume fraction and particle size of Al_3Ti, with a dense interface between matrix and reinforcements, improving mechanical properties of the composite compared to base metal [36]. Research of 10 wt.% B_4C–MoS_2 hybrid aluminum alloy composite, reinforced using the stir casting route, show that increasing share of MoS_2 reduces the hardness and toughness of hybrid composites but simultaneously, reduces the wear rate and friction coefficient of the hybrid composites [37]. The technique for stir casting with ultrasonic cavitation contains the following steps: first melted aluminum is stirred mechanically (400 rpm, for 10 minutes) and B_4C particles were added, after that ultrasonic probe was introduced, generating 20 kHz frequency ultrasonic vibration, for preparing micro and nanocomposites by varying

weight percentage of B_4C particles (2, 4, 6, 8, and 10 wt.%) [38]. By increasing the share of B_4C particles, up to 8%, the wear rate decreased significantly in the nanocomposites compare to micro composites [38]. In another study [39], the modified stir casting method was used to prepare aluminum alloy composites reinforced with B_4C, from 5 to 20 wt.%. Microstructure observation showed that increasing the share of B_4C particles affects their distribution along the dendrite arm, with clustering and agglomeration of reinforcements [39].

Al-Ti based particles reinforced aluminum-based metal matrix composites

Al-Ti based particles are used to enhance the mechanical and tribological properties of the aluminum-based systems. High-intensity ultrasonic vibration technique was used to fabricate aluminum alloy-based metal matrix composites reinforced with Al_3Ti [40]; it was observed by microstructure evaluation that fine Al_3Ti particles were evenly distributed in the α-Al matrix. Mechanical properties of composites were improved significantly due to evenly distributed Al_3Ti particles [40]. Powder metallurgy through hot pressing and hot extrusion was carried out to fabricate the lightweight composites reinforced with Ti-Al-Nb-B (TNM) [41]. Here, hot pressing was carried out at 400 °C with 600 MPa for 10 min, followed by hot extrusion at 700 MPa with 400 °C for 30 to 60 min depending upon TNM weight percentage. Precipitation of Si particles in the aluminum alloy matrix due to TNM reinforcements provided excellent bonding strength [41]. TNM reinforced aluminum alloy Al-12Si showed improvement in YS, UTS, and specific strength compare to base alloy [41]. Squeeze casting process (molten aluminum alloy at 760 °C was pouring in the steel mold followed by 15 MPa pressure for 30 minutes) was used to fabricate aluminum-based metal matrix composites reinforced with woven Ti_6Al_4V fabric for short solidification time [42]. TEM analysis shows that $TiAl_3$ as an interfacial reaction product and Ti-Al diffusion layer were formed ob interface during fabrication. Woven Ti_6Al_4V reinforced composites improved the hypervelocity impact strength of aluminum alloy [42]. Hotpress sintering methodology is a sintering process carried out at 620 °C, 40 MPa pressure with 1 hr holding time, and is used for fabricating aluminum composites reinforced with Ti_3AlC_2 and Cu coated Ti_3AlC_2 [43]. It was observed that Ti_3AlC_2 show poor wettability with aluminum [43].

TiC reinforced aluminum-based metal matrix composites

TiC particle reinforcement is used to enhance the mechanical and tribological properties of the aluminum-based systems. Nanocrystalline TiC powder with 35 nm in size was fabricated via the mechanical alloying method [44]. The hardness of material was relatively improved by preserving the nanocrystalline structure of TiC [44].

Al-Cu-Mg matrix composites reinforced with 5–9 vol.% nano-sized TiC_x particles fabricated by combustion synthesis (CS), and hot-pressing process combined with hot extrusion was presented in the literature [45]. Ball milled powder of aluminum alloy and reinforcements were set in the self-made furnace for compaction and combustion synthesis. Combustion synthesis happens when the temperature measured by the W5-Re26 thermocouple suddenly rose rapidly. The tensile strength, yield strength, and fracture strain of the composites (5 vol.% nano-sized TiC_x/Al-Cu-Mg) were simultaneously improved compared with base alloy fabricated via powder metallurgy at 300 °C [45].

TiB₂ reinforced aluminum-based metal matrix composites

TiB_2 particle reinforcement improves mechanical behavior, such as stiffness, strength, and wear resistance. Outstanding reinforcements occur because of its good thermodynamic stability, excellent resistance to mechanical erosion, high corrosion resistance, high melting point (2790 °C), high hardness (960HV), and low density [46-50].

The salt-metal synthesis route was successfully used to prepare Al-4.5Cu/5 vol.% TiB_2 composites: a modified mechanical stirring, where two kinds of pure salts KBF_4 and K_2TiF_6 were used for synthesis in the aluminum alloy melt at 830 °C for 30 minutes [46]. TiB_2 particles were uniformly distributed along the grain boundary in the matrix, and lots of dispersed particles with a size under 0.4 µm were also found. YS and UTS of the composites were enhanced by 85% and 46%, respectively [46, 47]. Salt-metal synthesis route was used to study [48] surface integrity (surface roughness, residual stress, microhardness, surface topology, and defects). The result shows that the feed rate was the dominant impact on surface roughness [48]. Besides, unlike aluminum matrix composites, pull out, or fractured particles were rarely found on the machined surface of in situ Al/TiB₂ composites [48]. Nanostructured Al5083 aluminum alloy-based composites with nano-TiB₂ reinforcement particles were fabricated via cryogenic grinding and spark plasma sintering (SPS) [49]. The interface between the aluminum matrix and n-TiB₂ appears to be free of defects and without apparent discontinuities. The strength was 20% higher than that of an equivalent SPs consolidated Al5083 without reinforcement [49]. *Haitao Chi et al.* [50] studied characteristics of friction and wear transition from the running-in stage to the steady-state stage for an aluminum-based composite containing TiB₂ particles and produced by a pressure infiltration technique (60 MPa, 770 °C molten aluminum alloy was infiltrated in the TiB₂ for 30 min). An increase of friction coefficient was caused by the abrasion of pulled out TiB₂ particles. Also, at a steady-state friction coefficient of 0.6, severe three-body abrasive wear and oxidative wear were the dominant wear mechanism [50]. The salt-metal synthesis route was used to fabricate Al/TiB2 in situ composites [51]. With EMS microstructure characterization, 80 to 90% of the TiB₂ particles were found to be in the range of 100-150 nm. The distribution of TiB₂ particles was almost homogenously near the solidified casting. Due to favorable microstructure features, consequent improvements in mechanical properties like hardness, tensile, and wear properties were achieved [51].

Graphene reinforced aluminum metal matrix composites

Recently researchers are highly attracted by graphene because a small addition of graphene (0.1 vol.%) leads to a significant change in mechanical and tribological properties of aluminum-based systems [52-54]. It is very much significant to find the consistent distribution of graphene in the matrix and to preserve the structure of graphene. *Xin Gao et al.* [52], fabricate aluminum matrix composites reinforced with GO (graphene oxide) sheets, using the powder metallurgy route. GO sheets were homogeneously absorbed on the surface of CTAB (coated by Cetyl trimethyl ammonium bromide) coated aluminum powder. UTS increased to some point, and after the addition of higher content of graphene begins to decline.

Spark plasma sintering method was used for consolidating the aluminum powder with graphene, hexagonal boron nitride (hBN), and molybdenum disulfide particles at 500 °C, with heating rate 225 °C/min, and dwelling time of 2 min with argon atmosphere

[53]. The friction coefficient decreased considerably, with an increase in 2D crystal particles [53]. High energy ball milling with vacuum hot pressing processes were used to fabricate aluminum matrix composites reinforced with graphene nanosheets (GNSs) [54], achieving good wettability and bonding strength of GNSs and aluminum; the Al_4C_3 phase with granular and rod-like morphology was found in the matrix. As graphene nanosheets increase in composites, the content of the Al_3C_4 phase was increased [54]. The YS, UTS of composites (Al-0.25GNSs) were increased compared to base aluminum [54].

Carbon fiber (Cf) reinforced aluminum-based metal matrix composites

Carbon fiber (Cf) is mostly used for improving the flexural strength of aluminum-based systems. Woven carbon fibers reinforced, Al–5Mg matrix composites were successfully fabricated by an electromagnetic casting process [55]. The casting results indicated that the contact time between the molten metal and the carbon fibers was vital to the bonding degree: increasing the solidification time reduces the cavity defects, located near the interface; however, an overly long solidification time would result in a tendency to crack in the centers of the woven fibers. Three-point bending tests showed that the bending strength of the composite had an improvement for 33.6% than that of the Al-alloy [55]. The development of a high-efficiency joining method of C_f/Al composites and TiAl alloys under the heat effect of laser-ignited self-propagating high-temperature synthesis (SHS) was reported in the literature [56]. The sound joint was obtained; with the joining pressure of 2 MPa and with additive filler metals: joint shear strength reached a maximum of 41.01 MPa [56]. C_f/Al composites were joined with Ti-Al intermetallic by a novel laser-induced self-propagating high-temperature synthesis joining method (SHS) [57]. A nanoscale thin Zr-C layer is formed on the $NiAl_3$/C_f interface, thus greatly improving the bonding quality on the C_f/Al side. Appropriate Zr content increases the joint density and enhances the wettability of the interlayer products on the carbon fibers. The joint shear strength under that condition reaches the maximum value of 68.71 MPa [57].

Figure 1 shows the recent literature trend for the most significant reinforcements in aluminum-based composites; the greatest attention is paid to SiC, Al_2O_3, and CNT reinforcements.
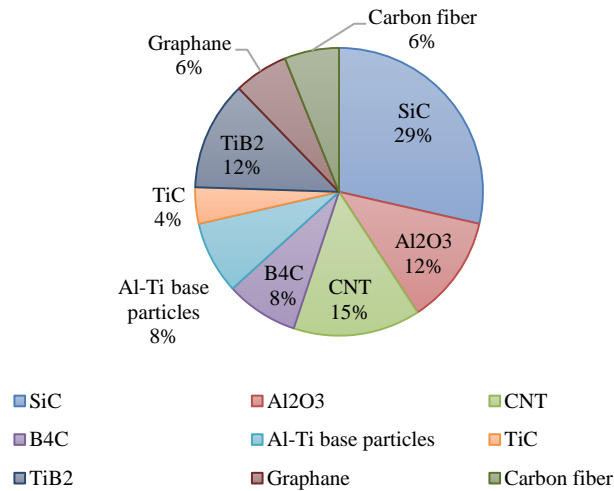
Fig. 1. Contribution of the reinforcements in aluminum-based systems [9-57].

Summary

Devoted research and development of aluminum matrix composites are observed in the advanced application of automobile structural, aviation industries, marine industries, shipbuilding, a critical component of space craft's where monolithic materials or alloys have its limitation to give right strength, stiffness, toughness, and density. Numerous process have been industrialized and applied to the fabrication of aluminum matrix composites, such mechanical stir casting, ultrasonic vibration-assisted stir casting, modified stir casting (two-stage), pressure and pressureless infiltration, powder metallurgy, selective laser melting (SLM), accumulative roll bonding (ARB), squeeze casting, hot pressing, spark plasma sintering (SPS), high pressure die casting, etc. Remarkable factors affecting the response of the aluminum matrix composites are the bonding strength of matrix and reinforcement interface, the chemistry, the size, shape, and distribution of reinforcement, and the matrix composition. SiC, Al_2O_3, TiB_2, B_4C, TiC, CNT, Carbon fiber, Graphite, Graphene, Al-Ti based particle, are some of the common reinforcements utilize to fabricate aluminum-based metal matrix composites (MMCs).

From Figure 1, it is observed that SiC [9-22] is frequently utilized as reinforcement. For improving mechanical and tribological properties, most common reinforcements are SiC, CNT, B_4C, Al-Ti based particles, TiC, graphene, and C_f. TiB2 is using for improving the compressing strength and serviceability of material at higher temperatures. Ductility of composites is reducing as the weight or volume fraction of the reinforcements increased, and simultaneously strength of composites is increased. Grain refinement is one of the popular ways to improve ductility and strength at ambient temperature: with smaller grain size, mechanical, tribological, and chemical properties were improved significantly; on the other hand, wettability and interfacial strength of matrix and reinforcements are also improved. The acceptance of the aluminum matrix

composites as engineering materials depends not only on the performance advantages of the composites, but it also depends upon the cheap, easy, and familiar fabrication technologies for these tailored materials.

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