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Review Article

Development of Aluminium Matrix Composites: A review

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Aluminium matrix composites (AMCs) are a range of advanced engineering materials that can be used for a wide range of applications within the aerospace, automotive, biotechnology, electronic and sporting goods industries. AMCs consist of a non-metallic reinforcement (SiC, B_4C, Si_3N_4, AlN, TiC, TiB_2, TiO_2) incorporated into Aluminium matrix which provides advantageous properties over base metal (Al) alloys. These include improved abrasion resistance, creep resistance, dimensional stability, exceptionally good stiffness-to-weight and strength-to-weight ratios and better high temperature performance. Fabrication of these advanced engineering materials through liquid state and solid state routes are considered in this paper.

Key Words: Metal matrix composites, aluminium, Silicon Carbide, reinforcement, A1/SiC.

INTRODUCTION

Metal matrix composites (MMCs) are a range of advanced materials that can be used for a wide range of applications within the aerospace, automotive, nuclear, biotechnology, electronic and sporting goods industries. MMCs consist of a non-metallic reinforcement incorporated into a metallic matrix which can provide advantageous properties over base metal alloys. These include improved thermal conductivity, abrasion resistance, creep resistance, dimensional stability, exceptionally good stiffness-to-weight and strength-to-weight ratios. They also have better high temperature performance. Hard and strong particles in the form of particulates or fibers are added to improve the thermo-mechanical properties and performance of the lightweight but comparatively soft host metal. Common reinforcement particles include ceramics such as silicon carbide and alumina, B_4C, Si_3N_4, AlN, TiC, TiB_2, TiO_2 and hard metals such as titanium and tungsten [1-4].

Aluminium Matrix Composites (AMC) is developed by reinforcing aluminium matrix with ceramic particles. AMC exhibits better mechanical properties than unreinforced aluminium alloys [5,6]. Aluminium is only second to steel,

when it comes to automobile body frame [7], with 5xxx and 6xxx series on the lead. Automobile aluminium alloys AA6111 (AlMg0.7Si0.9Cu0.7), AA6009 (AlMg0.5Si0.8CuMn), AA5251 (AlMg2Mn0.3) among others are currently in used while others are under development [7].

AMC Processing Routes

Particle reinforced metal matrix composites have already found commercial use on account of the fact that conventional processing techniques, such as powder metallurgy, vacuum hot pressing, co-spray deposition process, squeeze casting, and stir casting methods can be readily adopted for the processing of such materials [8]. There are various processing routes for aluminum with ceramics. A manufacturing technique (Figure1 and Figure 2) consists of vacuum infiltrating an A356 aluminum alloy into a SiC ceramic foam network [9]. Etter *et al*. [10] reported the production of interpenetrating graphite/aluminium composites by gas pressure infiltration of aluminium alloys with varying silicon content into porous graphite preforms. In this processing route, the porous graphite preforms were heated with the aluminium in an autoclave under vacuum of 30Pa. After achieving the infiltration temperature of 750^0 C, the liquid

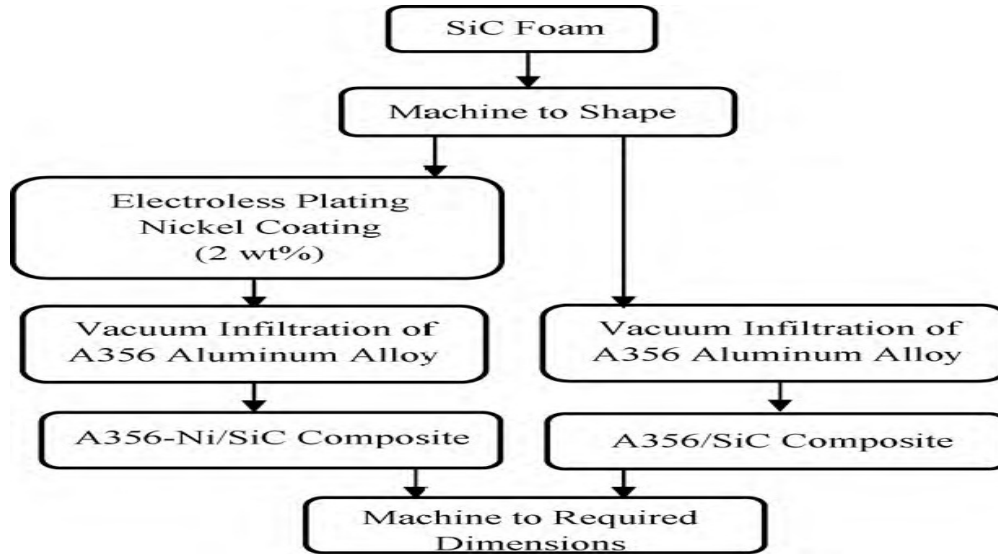*Corresponding Author's E-mail Address: phillip.babalola(at)covenantuniversity.edu.ng.

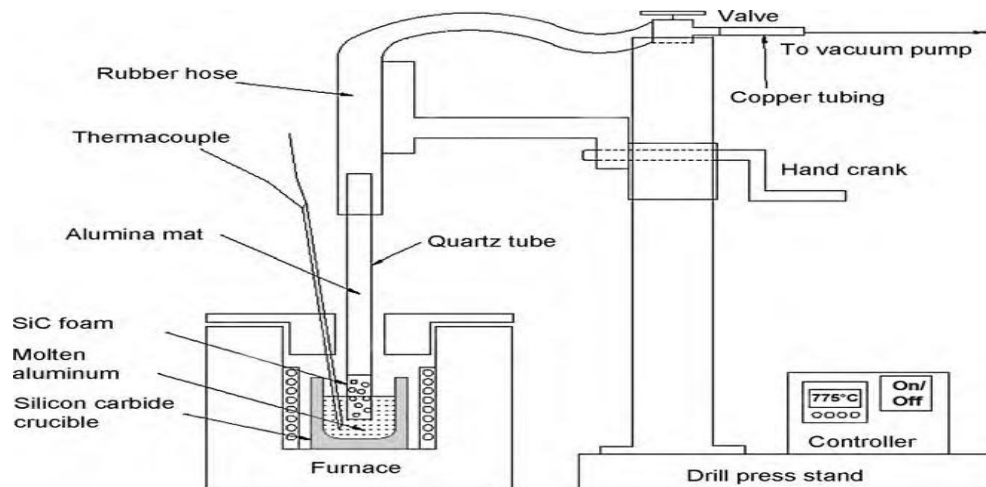**Figure 1.** Manufacturing procedure for the A356/SiC foam composite [9].

Figure 2. Schematic CAD diagram of the vacuum infiltration apparatus [9].

metal was pressed into the preform using inert gas at a pressure of approximately 8MPa. Fabrication of porous SiC ceramics for used in liquid metal infiltration were reported by Soy *et al*. [11]. Montoya-Dávila *et al*. [12] and Ortega-Celaya *et al*. [13] reported the preparation of Aluminium/SiC (particles) using pressureless infiltration.

Onat *et al*. [14] produced Aluminium composite by combining Al–4.5Cu–3Mg matrix alloy and 5, 10, and 15 vol.% SiC particle using squeeze casting method. Melting of alloy, degassing and additions of particulates were performed in an electrically resistance heated furnace. Graphite crucible was used for melting of matrix alloy, and the addition and mixing of particulates were made into the melt in the crucible. Casting operations were done at a constant pressure of 100MPa. Composite aluminium alloys (AA 2024 and AA 6061)) reinforced with Al_2O_{3p} particles have been produced by squeeze casting

followed by hot extrusion and a precipitation hardening treatment [8]. Another processing route is centrifugal casting. Pathak *et al*. [15] reinforced hypereutectic Al-Si alloy-based composite with SiC particles using centrifugal casting method. Huang *et al*. [16] used the same method to fabricate piston (Figures 3 and 4). The effects of various technique parameters, i.e., the slurry temperature of the alloy, the mold temperature and the rotation speed of the mold, on the particle segregation were investigated, and the macromorphologies and microstructures of pistons were observed. Rajan *et al*. [17] produced Al-SiCp functionally graded metal matrix composites (FGMMC) with graded distribution of SiC particles near the outer periphery of the casting using centrifugal casting method. They reinforced homogenous melts containing 356 and 2124 aluminum alloys with 15% SiC particles (Figure 5). Functionally graded metal matrix
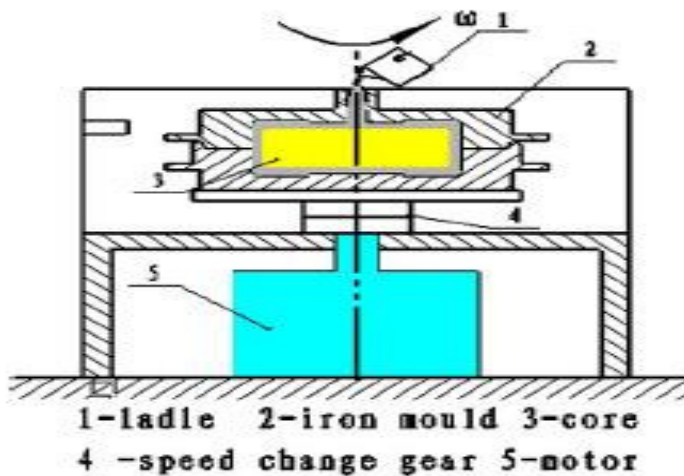
Figure 3. Schematic of the vertical centrifugal casting machine, Huang *et al*. [16].
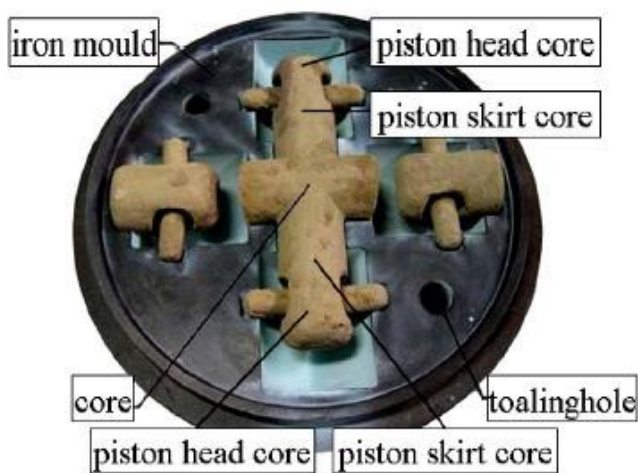

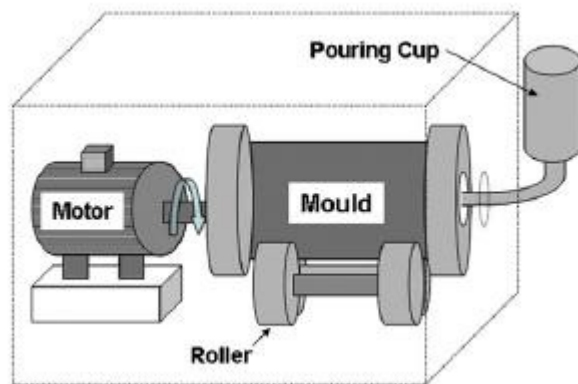**Figure 4.** Lower iron mold and cores [16].

Figure 5. Schematic diagram of horizontal centrifugal casting equipment used for fabricating FGMMC [17].

composites (FGMMC) are functionally graded materials (FGM) with metal and ceramic constituents, which are one of the most potential and prominent system for the design and fabrication of components and structures with gradient properties. FGMMC have superior capabilities for materials design and development of advanced engineering components.

Chaudhury *et al*. [18] prepared Al–2Mg–11TiO$_2$ composite using the conventional vortex method. The wet ability of the dispersoid (TiO$_2$) was improved by adding magnesium to the Aluminium matrix. The mechanical properties of the thermomechanically-worked composite were studied. From fractographic analysis, it was found that the crack had nucleated at the particle/matrix interface and propagated through the matrix by microvoid coalescence. Ultimate tensile strength of cold worked composite was found to be better than the hot worked material. Furthermore, the composite has greater hardness than the base alloy, arising from the presence of higher dislocation density in the matrix due to the difference in thermal properties between the matrix and dispersoids. Kathiresan and Sornakumar [19], combined aluminum alloy and silicon carbide particles using vortex method and pressure die casting technique. Molten temperature of 850^{0}C was used and stirring carried out for 45 minutes at the rate of 200 rpm. Silicon carbide particles were preheated to 200^{0}C and introduced into the vortex created in the molten alloy. The effects of varying casting temperature on the microstructure and wear resistance on A356/SiCp composites were investigated by Akhlaghi *et al*. [20]. Microstructural characterization studies conducted on the semisolid-liquid (750^0), SL, samples revealed a more uniform distribution of SiC particulates and less porosity content when compared to the semisolid-semisolid (590^{0}C), SS samples, regardless of the mould pre-heat temperature or the size and content of the SiC particles.

Eslamian *et al*. [21] used a technique based on centrifugal atomization for the preparation of metal matrix composites. An experimental setup (see figures 6 and 7) was constructed and aluminum powder and aluminum/ silicon carbide composite powder were prepared. The Al/SiC composite powder produced contained 18 vol.% of SiC particles and 1.2 vol.% of voids. Hrairi *et al*. [22] used powder metallurgy route to develop A356–fly ash metal matrix composites. The samples of this experiment were made of A356 aluminium containing 0, 5, 10, 15, 20 and 30 wt.% fly ash. Senthilkumar and Omprakash [3], on his part synthesised Aluminum composites reinforced with varying percentages of titanium carbide particles (TiC) produced through the *powder* metallurgy route. The composites consisted of pure aluminium (45 □m particle size) reinforced with 2.5% and 5% titanium carbide particles in as received condition from M/s Sigma Aldrich (fine size of 45 □m), compacted to a pressure of 300 MPa and sintered at a temperature of 500°C for two hours in a tube furnace under argon atmosphere. Basic characterization studies such as microstructure, X-ray
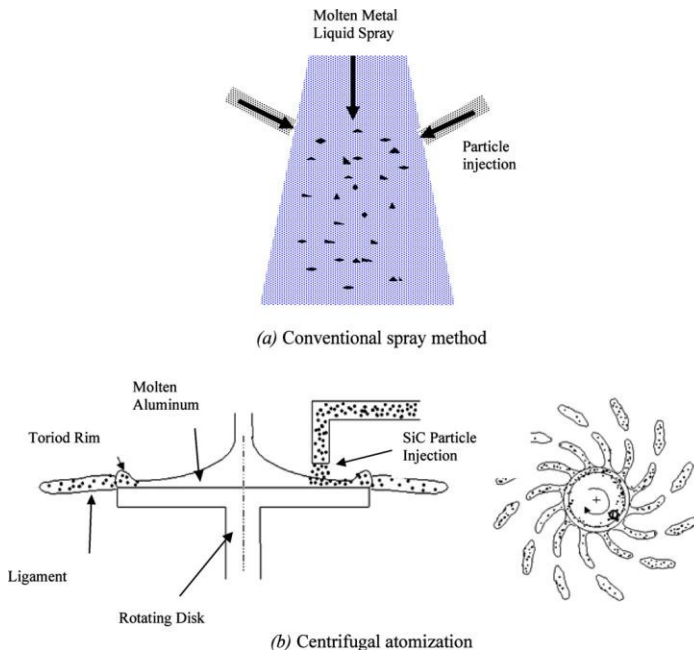
Figure 6. (a) Schematic of conventional spray method to produce MMC powders and (b) schematic of the new method for production of Al/SiC MMC: Centrifugal atomization with particle injection [21].
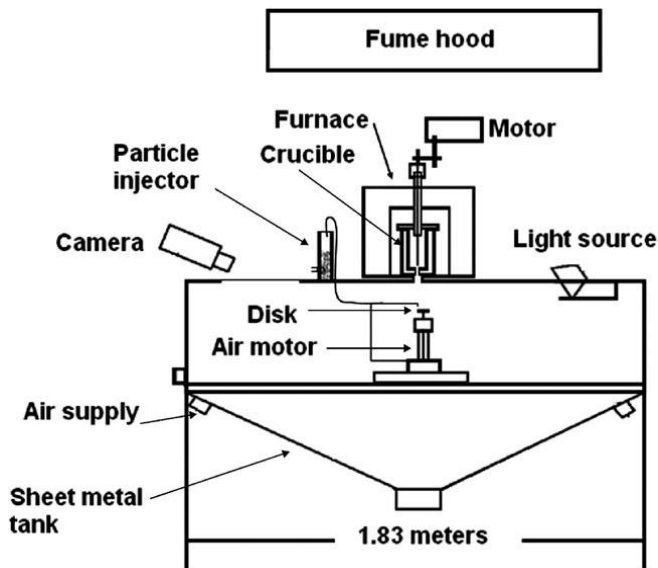

Figure 7. Schematic of the experimental apparatus [21].

diffraction pattern and hardness of sintered composites were conducted on the sintered composites to evaluate the material characteristics. Another researcher, Narayanasamy *et al*. [23], also used powder metallurgy (P/M) to produce Al-SiC composite. The effects of particle size of silicon carbide addition in P/M preforms of Al–SiC composite on workability were studied. The SiC content were varied from 0% to 20% with different particle sizes namely 50, 65 and 120 □m.

Also, cryomilling, a form of powder metallurgy method was used to combine boron carbide (B_4C) with Al 5083 to form a nano-grained metal matrix powder [24]. The addition of ceramic particulate reinforcement via cryomilling was found to significantly increase the physical and mechanical properties of Al alloys. This powder was blended with unmilled Al 5083 to increase ductility and was then consolidated into plates by three methods: (1) hot isostatic pressing (HIPping) followed by high strain rate forging (HSRF), (2) HIPping followed by two-step quasi-isostatic forging (QIF), and (3) three-step QIF. The effects of process method on microstructure and mechanical behavior for the final consolidated nano-composite plates were investigated. Thixoforming was also reported by Ozdemir *et al*. [25] in this method, composite powders were produced by high-energy ball milling (HEM) and then treated by semi-solid direct squeeze casting technique. Gas atomized AA 2017 aluminium alloy powders with a mesh size of ≤100μm were supplied as the starting matrix material for the processing route. The chemical composition of aluminium alloy matrix powder manufactured by gas atomization process is 3.9 Cu, 0.6 Mn, 0.7 Mg, bal. Al (wt.%). The aluminium matrix powder was mixed with volume fractions of 5 and 15% commercially available SiC or Al_2O_3 particles as reinforcement. The particle size ranges from 15 to 55μm for coarse reinforcements and from 0.2 to 2μm for fine reinforcements. Pre-mixed powders were milled by a laboratory scale high-energy ball milling unit of type Simoloyer CM08 (Zoz GmbH) within argon atmosphere using various rotation speeds (ranging from 600 to 800 rpm). The milling time was varied from 10 min to 3 h. The composite powders were cold pressed into a cylindrical shape and then heated up to a temperature range of 635–645^0 C in a permanent die, which is placed in an electrical furnace under an argon gas protective atmosphere. After the semi-solid state was achieved the material was finally solidified under a squeeze pressure of 100MPa to produce thixoformed samples. The samples were subjected to mechanical and metallographic tests.

A356-CNT composites were also produced by a special *compocasting* method using A356 aluminium alloy as the matrix and multi-walled carbon nano-tubes (MWCNTs) as the reinforcement. This was reported by Abbasipour *et al*. [26]. Their setup is shown in Figure 8. Compocasting method was also used by Amirkhanlou *et al*. [27] to produce Al6061/SiCp composites. The Al6061 alloy was melted in a graphite crucible of 1.5 kg capacity using an electrical resistance-heated laboratory furnace. The temperature of the alloy was first raised to 670^{0}C and then stirred at 500 rpm using an impeller fabricated from graphite attached to a variable speed AC motor. The temperature of the furnace was gradually lowered until the melt reached the liquid–solid state corresponding to 0.2 solid fractions while stirring was continued. At this temperature, a specific quantity of silicon carbide
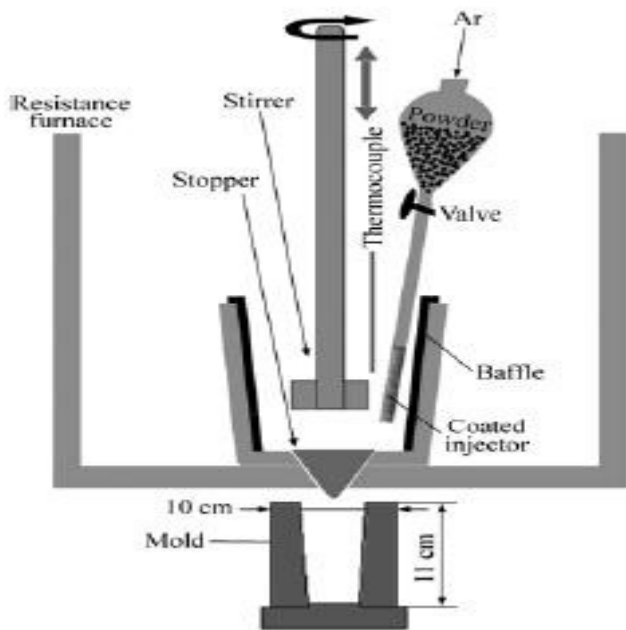
Figure 8. Schematic of experimental set-up used by Abbasipour *et al*. [26].
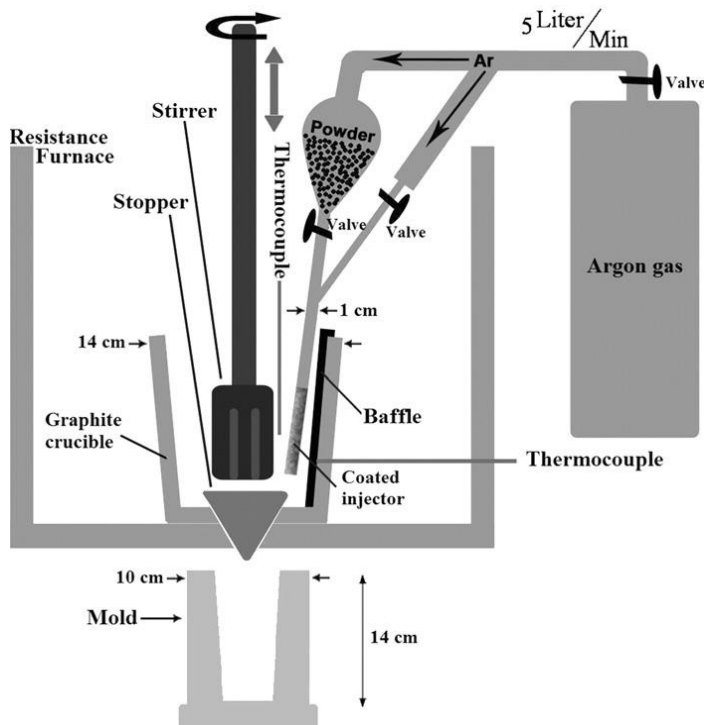

Figure 9. Schematic of experimental set-up used by Amirkhanlou *et al*. [28].

particles of 10 vol.% was added to the matrix alloy. Argon was used as the carrier gas for the injection of the reinforcements. After completion of the injection, the slurry was cast into a steel die placed below the furnace.
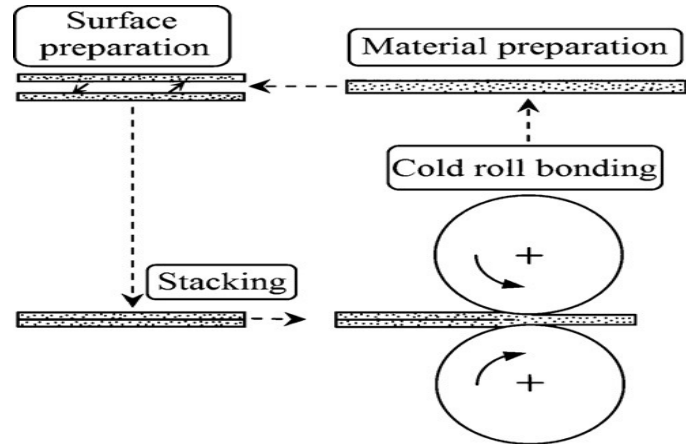

Figure 10. Schematic illustration of ARB process [28].

To improve the rolling capacity of as-cast composites, the annealing treatment (at 530^0C for 2 h) was performed before cold rolling process. Then, samples of 150 mm length, 50 mm width and 10 mm thickness were machined. The samples were then cold rolled with thickness reduction of 0.5 mm per each pass into different final reductions (30%, 60%, 75%, 85% and 95%) without any intermediate heat treating process. The rolling process was carried out with no lubrication, using a laboratory rolling mill with a loading capacity of 20 tons. The roll diameter was 125 mm, and the rolling speed was set at 2 m/min. They reported that the rolled specimens exhibited reduced porosity as well as a more uniform particle distribution when compared with the as-cast samples. Also, microscopic investigations of the composites after 95% reduction showed an excellent uniform distribution of silicon carbide particles in the matrix. During cold rolling process it was observed that the tensile strength and ductility of the samples increased by increasing the reduction content. After 95% reduction, the tensile strength and elongation values reached 306.7 MPa and 7.9%, which were 4.6 and 3.3 times greater than those of the as-cast composite, respectively.

Al356/10 vol.% SiCp composites were also produced by compocasting method [28]. Schematic of the experimental set-up used in the production of the cast composites is shown in Figure 9. Accumulative roll bonding (ARB) process (Figure 10) was then used to produce highly uniform distribution of Si and SiC particles in aluminum matrix resulting in high-mechanical properties. Placing Aluminium and SiC together for melting is experimentally a very convenient process. During the initial stage of heating, any moisture in the ceramic particles and the matrix materials is burn off and thus reduces the level of porosity. This advantage cannot be achieved by other methods in which the ceramic particles are introduced into the molten matrix material from the top [29]. The set up used for this arrangement is shown in Figure 11. Naher *et al*. [30] used A356 as the matrix material for the compocasting experimental work
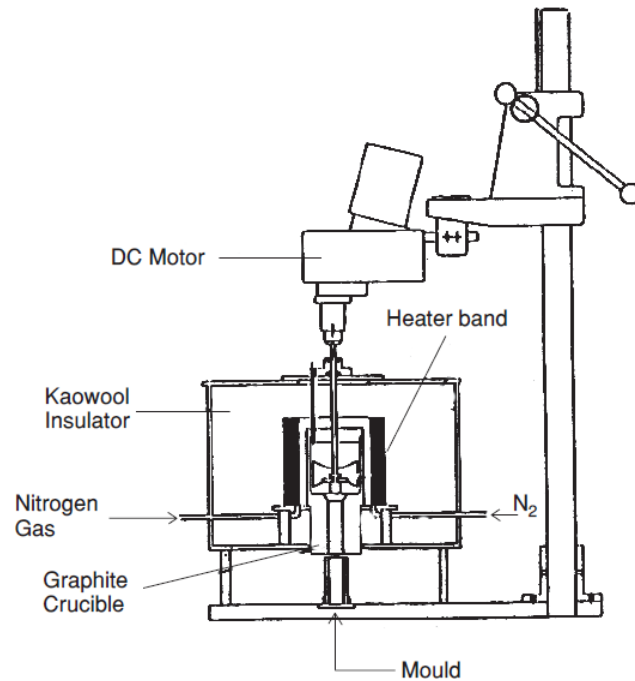
Figure 11. Rig used to produce cast MMC [29].
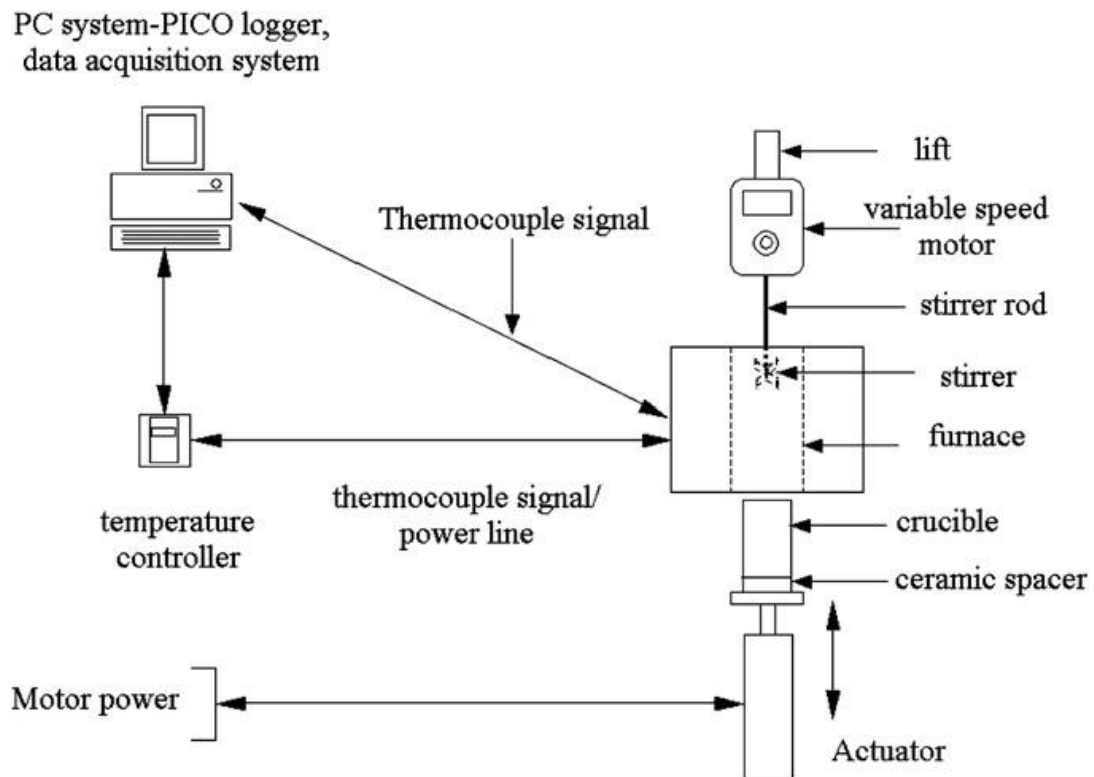

Figure 12. Schematic of constructed compocaster [30].

(Figure 12). At the start of each test, the 10% SiC was placed on the base of the crucible and cut to shape A356 ingot was placed on top of the SiC, to give a total height of 65 mm. The combination was then heated in the
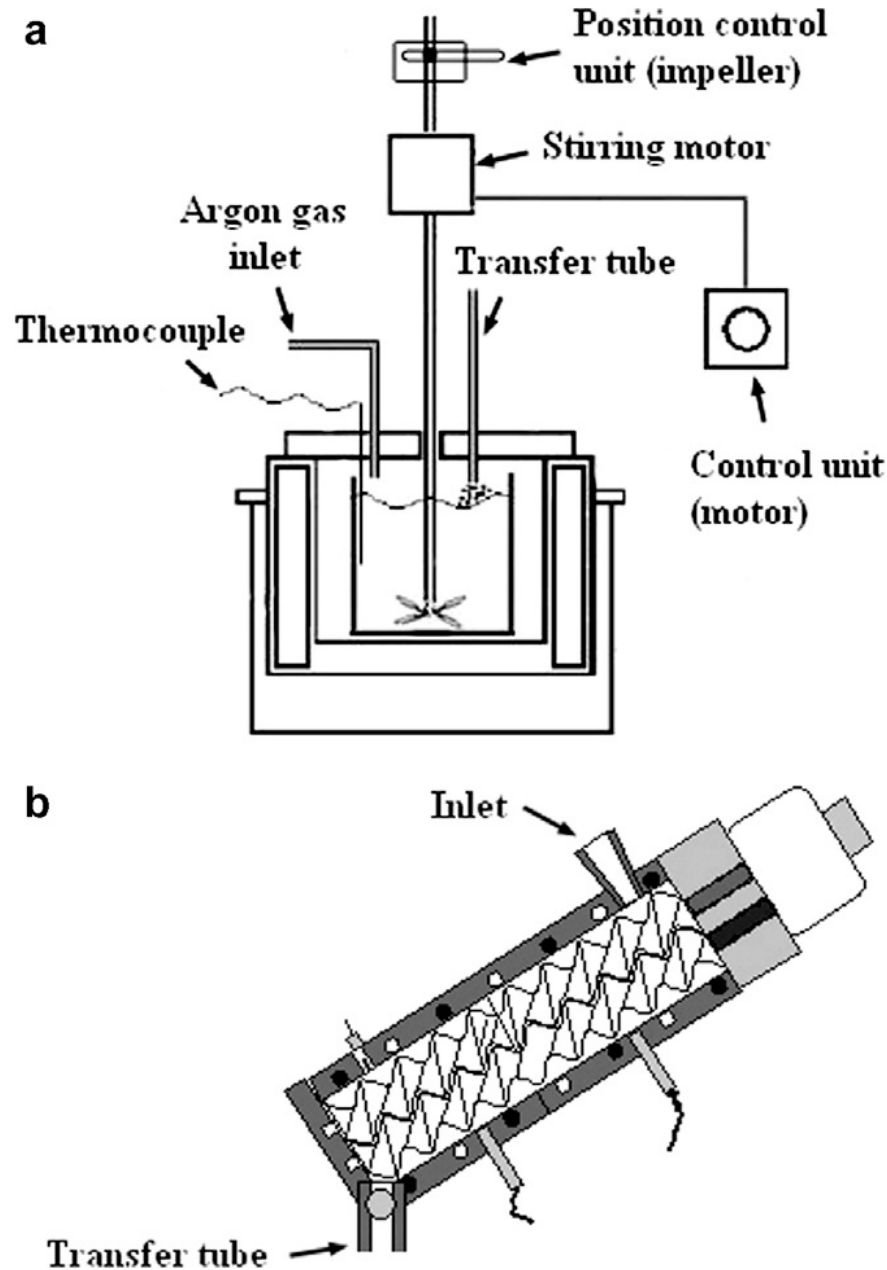
Figure 13. Schematic illustration of the mixing equipment used for (a) the distributive mixing process and (b) the Rheo-process [31].

furnace to 650⁰C and held for 30 min before the processing temperature was set and stirring commenced. This procedure, rather than introducing the particulate on top of the liquid or semi-solid metal, was found to provide consistently good particulate wettability. Tzamtzis *et al*. [31] produced A356/SiCp composites using a conventional stir casting technique and a novel rheo-process (Figure 13). The microstructure and properties were evaluated. The adopted rheo-process significantly improved the distribution of the reinforcement in the matrix. A good combination of improved ultimate tensile strength (UTS) and tensile elongation (e) was obtained.

Gopal *et al*. [32]; and Singla *et al*. [33] also used stir casting method. Singla et al. [33] started with manual mixing when the alloy was in a semi-solid state followed by automatic mechanical mixing for about 10 minutes at a stirring rate of 600 rpm in liquid state (see Figure 14).

Laser alloying, is a technique of localized alloy formation using laser surface melting with the simultaneous, controlled addition of alloying elements. These alloying elements diffuse rapidly into the melt pool, and the desired depth of alloying can be obtained in a short period of time. By this means, a desired alloy chemistry and microstructure can be generated on the
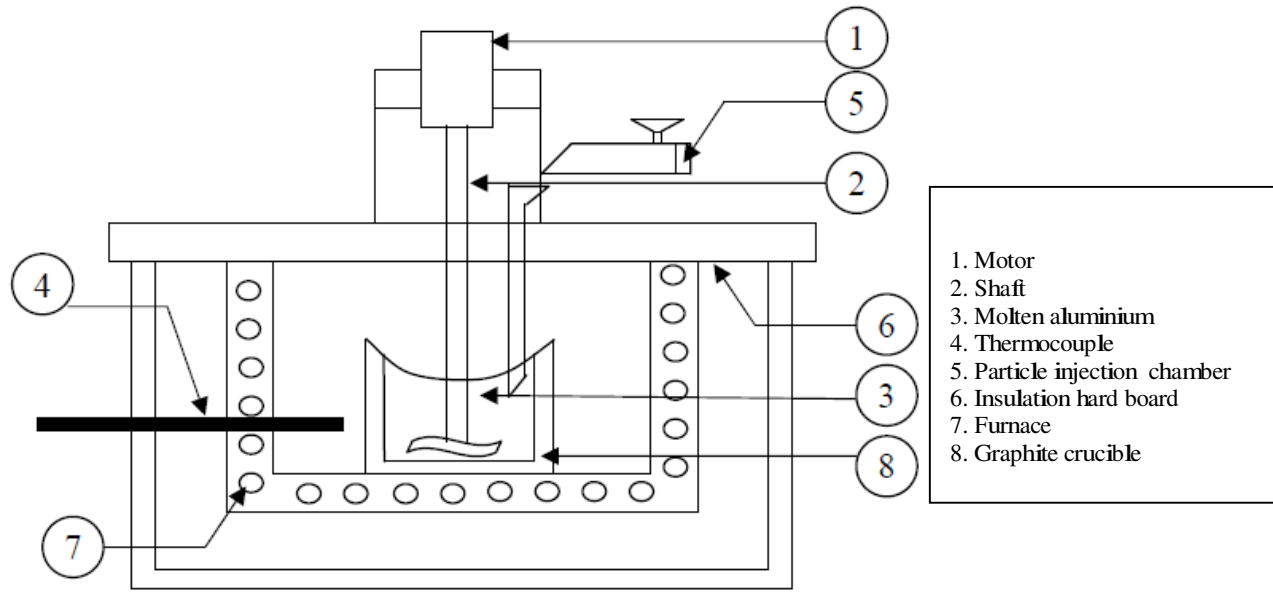
Figure 14. Schematic view of setup for Fabrication of composite [33].

sample surface; the degree of microstructural refinement will depend on the solidification rate. One method of alloying is to apply appropriate mixtures of powders on the sample surface, either by spraying the powder mixture suspended in alcohol to form a loosely packed coating, or by coating slurry suspended in organic binders [34]. Majumdar *et al.* [35] used this route (laser) to uniformly dispersed SiC particles in grain refined Al (with the presence of Al–Si eutectic at the grain boundary region) matrix. Qu *et al.* [36] studied the effect of SiC particle sizes dispersed in aluminium alloy. It was established that the particle size effect increases the plastic work hardening of the composite. Molecular dynamics simulations were carried out to characterize the interface of an Al–SiC metal matrix composite by Dandekar *et al.* [37]. An embedded atom model (EAM) and a Tersoff potential were used to simulate aluminum and silicon carbide respectively, while a Morse potential was successfully parameterized from ab initio data to represent the Al–SiC interface. Another investigator, Park *et al.* [38] used both liquid and powder metallurgy routes to combine Aluminium alloy and Al_2O_3. The high-cycle stress-life (S–N) curve and fatigue crack growth threshold (DK_{th}) behaviour of the composites were measured and compared. Jayaseelan *et al.* [39] also compared the performance characteristics of Al/SiC composites produced through stir casting and powder metallurgy. Stir casting specimen was found to exhibit high hardness compared to powder metallurgy specimen. Stir casting specimens also have finer grains in the microstructure than the powder metallurgy specimen. After extrusion both the extruded specimen exhibited reduced porosity, more uniform particle distribution, elimination of clusters and improved ductility and also both the specimens

experienced grain refinement and increased strength.

Guan *et al.* [40] produced hybrid Aluminium composite. Aluminum borate whisker (ABOw) and silicon carbide particle (SiCp) hybrid reinforced 6061Al matrix composites ((ABOw+SiCp)/6061Al) was fabricated by semi-solid mechanical stirring technique with different stirring temperatures and different stirring time. The influence of stirring parameters on microstructure and mechanical properties of the composites was investigated using scanning electron microscopy (SEM), X-ray diffractometry (XRD), transmission electron microscopy (TEM) and tensile tests. The results reveal that the homogeneity of reinforcement and tensile properties increased with decreasing the stirring temperature and increasing the stirring time. The optimal stirring parameters were 640 °C and 30 min. In recent years, experiments have shown that reducing the size of the particles to the nanoscale dramatically increases the mechanical strength of these composites even at low particle volume fractions [1,2]. These are referred to as metal matrix nano-composites (MMNCs). Law *et al.* [2] gave a summary of the effects of various quantities/ parameters on mechanical response of MMNC in Table 1

Applications of Aluminium MMC

Today, there is increasing use of metal matrix composites in the aerospace, automotive and bio-medical industries which resulted in the abundance of literature concerned with the processing, material characterization, properties, and manufacturing of these composites [37]. Though many desirable mechanical properties are generally obtained with fiber reinforcement, these composites exhibit anisotropic behaviour and are not easily

Table 1. Effects of various quantities/parameters on mechanical response of MMNCs [2].

Quantity/parameter	Initial yield stress, σ_{yield}	Flow stress, σ_{flow}	Degree of hardening, *n*
□ Density of dislocation sources, ρ_{nuc}	□	-	□
□ Strength of Dislocation sources, τ_{nuc}	□	□	-
□ Density of impurities, ρ_{obs}	-	-	□
□ Strength of impurities, τ_{obs}	-	-	□
□ Particle volume fraction	□	□	□
□ Particle size	-	□	□

Note: '-' indicates no significant effect, '□' indicates increase in mechanical property with increase in quantity/parameter, '□' indicates decrease in mechanical property with increase in quantity/parameter.

Table 2. AlSiC Material Properties Compared with Common Packaging, Substrate and IC Materials [41].

Material	Density (g/cm^3)	CTE ppm/^{o} (25-150^{0}c)	Thermal Conductivity (W/mk)	Bend Strength (MPa)	Young's Modulus (GPa)
Si	2.3	4.2	151		112
GaAs	5.23	6.5	54		
AlSiC (63V%SiC)	3.0	7.5	170-200	450	175
Kovar (Ni-Fe)	8.1	5.2	11-17		131
CuW (10-20%Cu)	15.7-17.0	6.5-8.3	180200	1172	367
CuMo(15-20%Mo)	10	7-8	160170		313
Cu	8.96	17.8	398	330	131
Al	2.7	23.6	238	137-200	68
SiC	3.2	2.7	200-270	450	415
AlN	3.3	4.5	170-200	300	310
Alumina	3.98	6.5	20-30	300	350
Beryllia	3.9	7.6	250	250	345

producible by conventional techniques. Nevertheless, MMCs reinforced with particles tend to offer modest enhancement of properties, but are more isotropic and can be processed by conventional routes [41].

Electronic packaging, Substrate, Heat sink and IC Materials

Aluminum Silicon Carbide (AlSiC) metal matrix composite (MMC) materials have a unique set of material properties that are ideally suited for all electronic packaging applications requiring thermal management. The AlSiC coefficient of thermal expansion (CTE) value is compatible with direct IC device attachment for the maximum thermal dissipation through the 170 – 200 W/mK thermal conductivity value of the material [9,42,43], see Table 2. Additionally, the low material density of AlSiC makes it ideal for weight sensitive applications such as portable devices.

Piston, Cylinder, Brake, Clutch and other high strength and wear resistance parts

In addition, Haung *et al*. [16] manufactured aluminum alloy-based composite pistons that were partially

reinforced with SiC particles by centrifugal casting. He reported that this type of piston contains a large quantity of SiC particles in the piston head, which can meet requirements such as hardness, wear resistance and the thermal expansion behavior of pistons. Majumdar *et al.* [35] deposited a thin layer of SiC and Al + SiC (thickness of 100 $\Box$m) on an Al substrate and laser irradiated using a high power continuous wave (CW) CO_2 laser. Irradiation leads to melting of the Al substrate with a part of the pre-deposited SiC layer, intermixing and followed by rapid solidification to form the composite layer on the surface. Following laser irradiation, a detailed characterization of the composite layer was undertaken in terms of microstructure, composition and phases. Mechanical properties like microhardness and wear resistance were evaluated in detail. The microhardness of the surface improves by two to three times as compared to that of the as-received Al. Another investigators, Rao *et al.* [44] examined dry sliding wear of aluminium alloy (Al–Zn–Mg) and aluminium (Al–Zn–Mg)–10, 15 and 25 wt.% SiCp composite under varying applied pressure (0.2 to 2.0MPa) at a fixed sliding speed of 3.35 m/s. The overall results indicated that the aluminium alloy–silicon carbide particle composite could be considered as an excellent material where high strength and wear resistance are of prime importance. Such applications are brake rotors and drums, brake calipers, cylinder liners, pistons, cylinder blocks, connecting rods, gear shift forks, clutch pressure plates, transmission components, turbocharger impellers, drive shafts, rotor tractor rails et cetera. These were already confirmed by Davis [45]. Suresha and Sridhara [46] studied the effect of graphite (Gr) particulates as a second reinforcement on the tribological behaviour of aluminium matrix composites reinforced with silicon carbide (SiC) particulates. The wear of hybrid composites (Al–SiC–Gr) decreases from 0.0234 g to 0.0221 g as the % reinforcement increases from 3% to 7.5%.

Conclusion

Aluminium matrix composites could be produced from Aluminium or its various alloys when combined with non-metallic reinforcing materials (SiC, B_4C, Si_3N_4, AlN, TiC, TiB_2, TiO_2 et cetera). The reinforcement could be particles, whisker, long fiber, short fiber or preforms. Various solid and liquid metal routes employed by myriad researchers were identified with indicative diagrams of the process. Stir casting, an example of liquid metal route was found to predominate because it is cost effective and processing parameters could be readily varied and monitored. Specimens from stir casting have high hardness and finer grains in the microstructure than the powder metallurgy one.

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