





The Advancement of Aluminum Metal Matrix Composite Reinforced with Silicon Carbide Particles (Al-6061/SiC_p): A Review

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Abstract. It is true that advancement in engineering and technology directly depends on the advancement of modified or new engineering materials. Now a day's Composite materials are receiving remarkable attention by enhancing the desirable properties of monolithic materials. Some product design requires a material that has a combination of two or more desirable properties in one, such as strength, hardness, wear-resistant, corrosion-resistant, good thermal and electrical conductivity, castability, machinability, etc. Metal matrix composites can satisfy the functional requirements of a specific product by varying the weight ratio of the selected metal matrix, and reinforced particles. Currently, aluminum matrix composite has a wide application in the production of enhanced automotive, aerospace, medical, and other machinery spare parts. This review paper mainly focused on the aluminum metal matrix composite which contains silicon carbide particles as reinforcement. In this review paper, different properties like mechanical, chemical, and physical properties (thermal and electrical conductivity) of the aluminum matrix composite are discussed, besides various types of manufacturing techniques, process parameters, applications, and future research gaps were studied in detail. This review paper specifically studies the effect of silicon carbide particles (SiC_p) reinforcement in the aluminum metal matrix and their related phenomenon.

Keywords: Metal matrix composite · Silicon carbide particles · Aluminum matrix composite

Nomenclature

AMMC Aluminum Metal Matrix Composite
MMC Metal Matrix Composite
SiC_p Silicon Carbide Particles

1 Introduction

1.1 Objectives of the Review

Currently, metal matrix composites synthesized from aluminum are widely used by industries for different applications. Because of its easiness to tailor to the desired functional requirements compare to other metal matrix composites. Hence, this review paper is studied to provide a detailed understanding of the advancement of composites of Al-6061 alloy with specific silicon carbide reinforcement and their major drawbacks in experimental research works. Throughout the review, the emphasis will be directed on Al-6061/SiCp composites of alternative manufacturing techniques, constraints of fabrication, the weight ratio of reinforcements, physical properties, mechanical properties, as well as identifying research scopes for further investigation.

1.2 Basics of Composite Materials

In the modern age, the development of large varieties of materials enables designers to be as creative as possible for new technology innovation based on a wide range of material properties [1]. With the recent advancement in the science and technology research areas, the property of the material can be enhanced and refined by using some reinforcing material is known as composite materials. It consists of a matrix and reinforcement in its composition. Matrix materials transfer the external exerted force to the reinforcement material which shields and maintain the shape of the matrix material. The reinforcement segment is the second segment of the composite material. The high stiffness and high strength of the composite material is accounted for by its reinforcement. The modern utilization of composites as engineering materials is evidenced by the real availability in the market from 1600 engineering materials more than 200 are composites [2]. Now a day's composite materials are emerging with a distinct technology that makes inspiration for the synthesis of new and stronger materials. The engineering materials of the composite are generally developed by mish-mashing of the selected group of materials that yield better properties than monolithic materials used alone. The physical and chemical characteristics of the matrix are the major factors to classify composite materials. These are metal-matrix, polymer matrix, and ceramic composites. A metal matrix composite (MMCs) offers better performance when it is compared to other classes of composite materials.

By combining the desirable attributes of metals and reinforcements, there is a possibility to have well-designed metal matrix composites for specific applications. The mechanical properties of newly developed composite materials are intermediate between the matrix alloy and the reinforcement when high strength and high modulus refractory particles are added [3]. The required physical and mechanical properties of the matrix should be considered for selection purposes. Commonly, Al, Ti, Mg, Ni, Cu,

Pb, Fe, Ag, Zn, and Sn are used as the matrix material, but Al, Ti, Mg are used widely for the development of AMMC [4]. Similarly, discontinuous fiber compounds such as SiC, Al₂O₃, and B₄C can be dispersed effectively in molten aluminum.

1.3 Aluminum Matrix

AMMCs have distinctive properties such as high strength to weight ratio, good mechanical properties, and better durability. Hence, the demand for this material is highly increased in many manufacturing industries from time to time. Aluminum matrix composites are the most researched MMC which are commonly applied in automotive construction, aerospace, and other industries. AMMCs are widely used due to their high specific modulus, strength, and wear [2]. In particular, it has been reported that by increasing the weight ratio of reinforcement particles, AMMCs possess improved wear resistance and lower friction coefficient when it is equated to monolithic aluminum alloys.

1.4 Reinforcements

Reinforced material is that the main member of the composite family which bears the load over the matrix material. Reinforcement materials enhance the specified mechanical properties within the material during a discriminatory direction like strength, stiffness, hardness, etc. There are many sorts of reinforced particle which are selected depends on the specified property of the aluminum matrix composite materials. Particularly, reinforcements utilized in AMMCs are considered as continuous fibers, short fibers, whiskers, and equiaxed particles. The diameter of reinforcements also can vary widely from about 0.01 μm to 100 nm. If the ratio of length to the diameter of fibers lies above 100, they will be utilized in applications where higher specific strength and specific modulus are required. In particulate composites, the ratio of length to diameter approaches one [5]. Particle-reinforced MMCs differ from normal dispersion-hardened materials during which the particle size varies between 0.001 to 1 μm . The possible interparticle gap for MMCs is smaller than 5 μm , and therefore the weight ratio of the particulate is additionally less than 0.10 [5].

The weight percent of reinforcement highly affects the mechanical and physical characteristics of developed composites [6]. Numerous investigators have assessed that the quantity fraction of reinforced particles is below 30% is going to be used for structural and machining uses [7, 8]. Table 1 presents the common selection of mishmashes of aluminum metal matrix alloy and therefore the fiber dispersoids that are wont to produce cast MMCs, especially for the car industries.

Table 1. The possible AMMC and dispersoid combinations [9].

Matrix	Dispersoid	Size (μm)	Amount
	Graphite flake	20–60	0.9–0.815%
	Graphite granular	15–500	1–8%
	Shell char	125	15%
	Al_2O_3 particles	3–200	3–30%
	Al_2O_3 discontinuous	3–6 mm long, 15–25 μm dia	0–23 vol%
	SiC particles	9–12	3–60%
	SiC whiskers	5–10	10%, 0–0.5 vol%
	Mica	40–180	3–10%
	SiO_2	5–53	5%
	Zircon	40	0–30%
	Sand	75–120	36 vol%
	TiC particles	46	15%
	Boron nitride particle	46	8%
	Si_3N_4 particle	40	10%
	ZrO_2	5–80	4%
	TiO_2	5–80	4%
	TiB_2	2–10	3–9 wt%
	C_{SF}	3–5 mm %	1–3 volume

In AMMCs, the second phase like fibers, whiskers, and particulates are incorporated in aluminum alloys to realize properties that aren't obtainable in conventional monolithic materials. The main properties enhanced in MMCs are mentioned as a specific strength, specific modulus, toughness, fatigue, creep, electrical, thermal properties, and wear resistance. These are often achieved by selecting logically the reinforcement materials, their size, shape, and weight ratio. Among many dispersoids, silicon carbide particles are the foremost common reinforcement in AMMC due to their easy availability and manufacturability. AMMCs reinforced with silicon carbide can possess wear and thermal shock resistance, good mechanical properties, and also high working temperatures. When embedded in metal matrix composites, SiC certainly improves the general strength of the composite together with corrosion and wear resistance. The addition of SiC particles in aluminum MMCs increases 20% improvement within the commonest mechanical properties of materials [9]. Most properties of aluminum metal matrix and carbide reinforcements are summarized in Table 2.

Table 2. Summary of properties of candidate materials [9–11].

No.	Properties	Al-6061 T6	SiC
1	Density (Kg/m ³)	2700	2900
2	Melting temperature (°C)	660	2830
3	Thermal conductivity (W/m.K)	180	120–170
4	Coefficient of thermal expansion (ppm/K)	23	4.9
5	Electrical conductivity (% IACS)	43	3
6	Tensile Strength (MPa)	300	470
7	Compressive strength (MPa)	260	896
8	Hardness (BHN)	75	140
9	Tensile failure strain (%)	10	<0.1
10	Modulus of elasticity (GPa)	60	520
11	Machinability ratings	1.9	–

1.5 Manufacturing Techniques of Aluminum Metal Matrix Composites

The liquid state process of producing methods of the AMMCs are talking about as stir casting, compo casting, squeeze casting, spray casting, and in place (reactive) processing, ultrasonic-assisted casting. Alternatively, the Solid-state manufacturing process comprises powder metallurgy, high-energy ball milling, friction stir process, diffusion bonding, and vapor deposition techniques (Table 3).

Table 3. Comparative study of different fabrication processes to AMMCs [12, 13].

No.	Process	Shape	Size	Volume fraction	Reinforcement condition	Cost
1	Stir casting	Wide range of shape	Larger size up to 500 kg	Up to 0.3	No damage	Least expensive
2	Squeeze casting	Limited by performing shape	Up to 2 cm height	Up to 0.5	Severe damage	Moderate expensive
3	Spray casting	Limited shape	Large size	Up to 0.7	Reinforcement damage	Expensive
4	Powder metallurgy	Wide range	Restricted size		Reinforcement fracture	Expensive

Stir casting technology is being considered for future research because of its lower cost compared to the available manufacturing techniques of AMCs [14]. The commercial widespread of the composite material stir casting route is most suitable to achieve a good quality of composite materials. It is also accepted commercially due to the low cost of processing in comparison with other processing methods, and its flexibility. A good dispersion of reinforcement particles without damaging the reinforcement can be realized by controlling the stir casting parameters.

The aluminum matrix hybrid composite materials are preferably used for many automobile and aerospace spare parts such as driveshaft, engine block, engine liners,

gearbox components, rotors, brake components, etc. Apart from these, many researchers have found several difficulties in fabricating the composite material. The most commons are poor chemical reaction between the reinforcement and matrix alloy, lack of wettability between reinforcements and matrix, sponginess in the cast MMCs, and problem in achieving a uniform distribution of the reinforcement material. However, MMCs can allow researchers to have optimal desirable properties as per the functional requirement of the product however there should be management and monitoring of process variable parameters to get the required output.

2 Materials and Methods

Generally, because of a large demand for advanced engineering materials to meet the design requirements of a product, many scholars and researchers were involved in the synthesis and characterization of metal matrix composites from ancient to recent. It means that scientific pieces of evidence and references can be accessed now a time for further investigation in this area. Especially aluminum metal was the most common metal matrix material because of its abundancy and suitable engineering properties for the most required functional requirements. Hence, the methodology to review this paper is performed primarily through surveys and summaries of previously published studies of the subject in aluminum metal matrix composites (AMMCs) from consistent websites. It comprises journals, peer-reviewed articles, books, dissertations, and conference proceedings.

3 Previous Research Works on Al-6061/SiC_p Composites

Many research works were conducted by many scholars and researchers on aluminum matrix composites for a long time. Some of them are presented below (Table 4).

Table 4. Summary of previous research works in Al-6061/SiC_p composites

No.	Authors (year)	Materials and methods	Results	Ref.
1	Chen et al. (2009)	<ul style="list-style-type: none"> Al-6061 + 5% SiC + 5%Gr Stir casting 	<ul style="list-style-type: none"> At 300 °C, the developed composite has higher thermal conductivity (163 W/m.K) than P20 steel (42 W/m.K). It can be an improved mold tooling for plastic materials 	[12]
2	Prabu et al. (2006)	<ul style="list-style-type: none"> High silicon content aluminum alloy Silicon carbide metal matrix composite material, with 10%SiC Brinell hardness test SEM 	<ul style="list-style-type: none"> The particle clustering becomes lower when the stirring speed and time increased, and vice-versa was true during microstructure analysis In addition, at a stirring speed of 600 rpm, uniform hardness was seen and it degraded beyond this speed 	[15]
3	Veeresh Kumar et al. (2010)	<ul style="list-style-type: none"> Al-6061-SiC Liquid metallurgy 	<ul style="list-style-type: none"> Hardness, strength, density, and wear resistance increased 	[16]

(continued)

Table 4. (continued)

No.	Authors (year)	Materials and methods	Results	Ref.
4	Mazahery and Shabani (2013)	<ul style="list-style-type: none"> The experimental specimens were prepared from the average size of 15, 20, and 50 μm SiC and a weight ratio of 5%, 10%, and 15% to determine microstructure and wear characteristics Management of stir casting factors like temperature of pouring, speed, time, and pre-heating temperature of particulate fibers Composting method 	<ul style="list-style-type: none"> Rolling operation after stir casting can reduce porosity defects of composite The hardness of tested materials increases with the increase of SiC particles amount No more plastic deformation was seen on the worn-out surface of this composite material 	[17]
5	Nair and Joshi (2015)	<ul style="list-style-type: none"> Al-6061 as the matrix and silicon carbide (10%) was used Stir casting SEM 	<ul style="list-style-type: none"> SiC particles were dispersed nicely while it is analyzed using SEM Minimization of porosity and improvement of wettability can be obtained by adding magnesium powder 	[18]
6	Mishra and Srivastava (2016)	<ul style="list-style-type: none"> Aluminum Al-6061 matrix and a mesh size of 150 and 600 SiC particles The weight ratio of SiC in a specimen seriously varies as 5, 10, 15, 20, 25, 30, 35, and 40% Stir casting method 	<ul style="list-style-type: none"> Regardless of mesh size, the wear resistance increases with an increasing volume fraction of particles An optimal result has been obtained at a 35% weight fraction At 600 mesh size of SiC particle, wear rate and coefficient of friction were decreased more relative to 150 mesh size 	[19]
7	Natrayan et al. (2018)	<ul style="list-style-type: none"> Alloy aluminum as matrix and SiC particles as fiber, Leaf ashes used as the reinforcement Bottom pouring stir casting method 	<ul style="list-style-type: none"> The addition of leaf ashes minimizes the wear rate of base metal The hardness of the Al-6061 with the SiC reinforcement has been increased 	[20]
8	Murugan et al. (2018)	<ul style="list-style-type: none"> Al-6061 alloy SiC 20-micron size and weight ratio (5, 10, and 15%) Stirring speed (300, 350 & 400 rpm) Fly ash (3%) stir casting Design of experiment (DOE) method Taguchi method for predicting the better parameters 	<ul style="list-style-type: none"> Stir casting parameters such as time (2, 4 & 6 min), speed (300, 350 & 400 rpm) were wide-ranging to cast the vital specimens The tensile strength value increases with the increase in wt. % of SiC and stirring time Tensile strength decrease with the decrease in stirring speed 	[21]
9	Dwivedi and Sahu (2018)	<ul style="list-style-type: none"> Aluminum (Al-6061) based metal matrix composite successfully developed using SiC as reinforcement Electromagnetic stir casting route Three parameters (preheat temperature, size, weight percent) of SiC were selected 	<ul style="list-style-type: none"> The corrosion rate decreases by enlarging the preheat temperature of SiC Increasing the particle size and weight percent of SiC, the corrosion rate also increases Uniform distribution of composite was observed at optimum SiC particle parameters 	[22]

(continued)

Table 4. (continued)

No.	Authors (year)	Materials and methods	Results	Ref.
10	Kumar et al. (2019)	<ul style="list-style-type: none"> Al-6061 and SiC are used as a composition of specimens (i.e. weight ratio of 5%, 10%, and 15%) EDM machining was used to test surface roughness 	<ul style="list-style-type: none"> An improved surface finish was found at a composition of aluminum 6061 with a SiC 10% weight ratio 	[23]
11	Kumar Maurya et al. (2019)	<ul style="list-style-type: none"> Determination of the influence of the composition of SiC on aluminum alloy Al- 6061 The weight percent of SiC content was varied (0, 1, 2, 3, and 5%) stir casting method 	<ul style="list-style-type: none"> By varying weight percent up to 5 wt% of SiC particles, the physical and mechanical characteristics like density, tensile strength, and hardness of composites were significantly improved 	[24]
12	Bhat and Kakandikar (2019)	<ul style="list-style-type: none"> Al-6061 and 5% SiC (50 μm size) were used for ingredients The stir casting method is used for specimen fabrication A Pin on disc tribometer with a load range of 5N-200N and RPM varying from 200 to 1500 was used for wear characteristics studying 	<ul style="list-style-type: none"> At a limited RPM, Wear-resistant decreases fastly when RPM increases in case of Al-6061 testing than Al-6061/SiC Reinforced Al-6061 with SiC particles has better mechanical characteristics than an unreinforced alloy 	[25]
13	Soltani et al. (2017)	<ul style="list-style-type: none"> Aluminum ingot with 99.8 in wt. % commercial purity and weight ratio 3% SiC composites were used as constituents to fabricate composites at two casting temperatures (680 and 850 $^{\circ}\text{C}$) The stir casting method and stirring times (2 and 6 min) were applied SEM and HRTEM were used to test porosity, ceramic incorporation, and agglomeration of the particles 	<ul style="list-style-type: none"> An optimal stirring time is controlled to realize the desired metal and ceramic bonding at the interface Improved ceramic incorporation was also found at higher stirring temperature (850 $^{\circ}\text{C}$) In addition, uninvited defects like shrinkage, porosity, and intensive formation of Al_4C_3 at the metal and particles interface were observed A better Al/SiC bonding at 680 $^{\circ}\text{C}$ was caused by the formation of Al_4C_3 	[26]
14	Pandiyan and Prabaharan (2020)	<ul style="list-style-type: none"> Al-6061 T6 matrix and SiC (0, 5, 10, and 15 wt. %) were varied in the experiment works Mechanical characteristics like density, tensile, compression, hardness, and impact strength were tested and evaluated A dry sliding wear test was applied to determine the tribological behavior of the composites Taguchi-based L'27 orthogonal array with input parameters such as SiC (wt. %), Sliding Distance (m), and load were considered to measure tribological behavior SEM and energy dispersive X-ray analysis (EDX) were used to determine the dispersion of SiC in the Al-6061 T6 matrix 	<ul style="list-style-type: none"> When SiC constituents were increased in the Al-6061 T6 matrix, the physical properties like density values were increased When SiC was added at 15 wt. % to Al-6061 T6, maximum tensile strength, compression strength, impact strength, and hardness values were evaluated The existence of SiC particles in the composite counterattacked the wear of the material. When SiC was added at 15 wt. % there was enriched wear resistance The sliding distance was the dominant factor that was ensured by ANOVA during tribological studies 	[27]

By and large, a nonstop requirement for upgrades in AMMCs properties across a wide scope of uses is extremely high in numerous spaces like transportation, aviation, military designing, and so forth. A particular prerequisite is the advancement of lightweight high strength materials with improved mechanical properties. This can be accomplished by fostering another class of materials to meet the difficult issues presented inside engineering applications. The ideal redid mechanical properties can be conferred in metal framework composites. The choice of the creation technique for making the composite impacts the material conduct. The assembling strategies of AMMCs have an impact not just on the support circulation, homogeneity, bunching/agglomeration, wettability, hardness dispersion, and thickness dissemination, and so forth yet additionally on the mechanical conduct of the integrated material.

4 Recommendation and Future Works

The major selected research necessities in aluminum metal matrix composites while different manufacturing techniques applied are mentioned below:

- In stir casting, Prevention of agglomeration and clustering of micro and nano-sized reinforcements are important in aluminum metal matrix composites.
- The growing interface is also required to achieve uniform distribution of reinforcements in the matrix with good bonding, and involving engulfment of reinforcements.
- In situ reinforcements, using low-cost reinforcements and low-cost processing are recommended to reduce the cost of components.
- Machining difficulty has been observed in cast aluminum metal matrix components; hence further research is required to get optimal machining parameters.
- Developing a guiding principle to recycle aluminum metal matrix components at completed its usage life is also another research area.
- Agricultural and industrial waste like fly ash as fillers should be used to develop cheaper stir cast components with low exemplified energy.
- Developing manufacturing capability and user base for smart metal matrix castings including self-healing, self-lubricating, and shape recovering aluminum matrix composites are timely required.
- Improvement manufacturing methods of Al-6061 nanocomposites through stir casting should be one of the focus areas of future studies.

5 Conclusion

The quick development of designing and innovation straightforwardly relies upon the development of current materials. Aluminum metal matrix composites (AMMCs) have acquired huge consideration lately. The significant justification for its more popularity is a direct result of its lightweight, low coefficient of warm development, great machinability, and improved mechanical properties, for example, yield pressure, extreme elastic pressure, and hardness. Inferable from these benefits, they are utilized

in aviation parts, automobiles, electronic segments, and other industrial machine components. Mix projecting (vortex strategy) is by and large acknowledged monetarily as a minimal expense technique for the manufacturing of AMMCs. Its motivations rely upon its simplicity, manageability, and relevance to large-scale manufacturing. The vortex strategy is less expensive than the existed methods for AMMCs creation, and it permits huge measured parts to be manufactured. Consequently, this audit paper stresses the investigation of aluminum matrix composite that would accomplish ideal consolidated attractive properties, for example, wear-safe, thermal conductivity and electric conductive, and great machinability for various applications. Due to the requirement for lighter-weight, wear-resistant, and higher thermal conductive segments, the interest for MMCs will keep on developing. Significant boundaries to the development of cast AMMCs incorporate significant expense, absence of plan information, and trouble in machining, setting up huge volume assembling, and reusing. Aluminum matrix composites cast to date incorporate aluminum-silicon carbide, aluminum alumina, aluminum graphite, and aluminum fly debris. A few projecting strategies including sand, speculation, lasting mold, crush projecting, radiating projecting, and removal projecting have been utilized to project metal matrix composite parts. Notwithstanding miniature composites, late work has been directed to create aluminum metal framework nanocomposites, syntactic froths, self-greasing up, and self-healing castings.

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