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Review Article

Aluminium hybrid composites: A review of reinforcement materials and reinforcement philosophies

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ABSTRACT: Aluminium hybrid composite reinforcement technology is a response to the demands of advanced engineering materials. The motive behind the use of aluminium hybrid components in the transport, agriculture and mining sectors is based on the requirement for weight reduction and in pursuit of high efficiency and performance at a reduced cost. The performance of these materials is largely dependent on selecting the right combination of reinforcing materials, since most of the physical, chemical, mechanical properties and processing parameters such as particle size, weight percent of reinforcement and fabrication method were largely associated with the reinforcement. This paper attempts to review the different materials that have been used as reinforcements and the reinforcement philosophy adopted by several researchers with a view to establishing the effects of the reinforcement materials on micro structural, mechanical and tribological properties of hybrid composites. The processing methodology and its effects on aluminium hybrid composites have also been reviewed with a view to suggesting the best applications of aluminium hybrid composites.

Keywords: Advance engineering materials, improved efficiency and performance, microstructure and mechanical properties, processing parameters, weight reduction.

INTRODUCTION

Recent worldwide interest in the field of materials has been directed towards the need to have low weight and density, while still retaining high strength and performance especially in structural and transport industry. In structures, low weight and high strength enables the building of high rise buildings which can withstand adverse environmental conditions imposed by weather. While in transport industry, weight carries a fuel penalty, modest for automobile, greater for trucks and trains, greater still for aircraft and enormous space vehicle. Increased fuel combustion implies increased emission of CO_2 to the atmosphere and the consequent harm to the environment (Ashby *et al.*, 2018). Also with the emergence of hybrid vehicles, the need to reduce weight has become tremendously necessary considering available power for propulsion.

Another current challenge is the need to produced materials at a reduced cost of production with respect to raw materials and the need to recycle waste materials into new products, that way ensuring the development of environmentally friendly materials and sustainable development as required by the United Nations Developmental Goals (Llopis–Albert *et al*., 2022; Alaneme and Adewale 2013). Composites materials have been found to be a reliable solution for such materials requirement. In composites, the reinforcement materials are combined in such a way, to enable the product material have better use than the parent materials. The term composite gives indication of the combination of two or more materials in order to improve properties. Driving force for the utilization of composite in structural materials and transport industry include performance, economic, and environmental benefits (Bhandare and Sonawane, 2013; Alaneme and Adewuyi, 2013).

The parent or base material whose properties are to be improved on is usually referred to as the matrix, while the materials used to improve these properties are known as the reinforcements. The main function of the matrix is to transfer and distribute the load to the reinforcements. This transfer depends on the type of matrix materials, reinforcement and the fabrication technique. The matrix is usually selected on the basis of oxidation and corrosion resistance, density, chemical compatibility, mechanical properties and a host of other requirements (Escalera–Lozano *et al*., 2007).

Generally, Al, Ti, Mg, Ni, Cu, Pb, Fe, Ag, Zn, Sn and Si are some of the metals used as the matrix material, but Al, Ti, Mg are mostly used for light weight applications (Bobic *et al.*, 2010). Nowadays, researchers all over the world are focusing mainly on aluminum because of its unique combination of good corrosion resistance, low density and excellent mechanical properties (Bhandare and Sonawane, 2013; Bobic *et al.*, 2010). The unique thermal properties of aluminum such as metallic conductivity with coefficient of expansion that can be tailored down to zero, wide alloy range, heat treatment capability, design and processing flexibility, strong bonding at the interface of matrix and reinforcement add to its prospects in the development for composites for structural materials, transport industry, aerospace and avionics to mention a few. For instance, elastic modulus of pure aluminium can be enhanced from 70 to 240 GPa by reinforcing with 60 vol.% continuous alumina fiber (Bhandare and Sonawane, 2013). Similarly, it is possible to process aluminum reinforced with 9 wt% of Al_20_3 and 20 wt% of SiC_p to produce composites having wear resistance equivalent or better than that of grey cast Iron (Aigbodion *et al.*, 2010). These examples and more illustrate that it is possible to alter several, physical, mechanical and chemical properties of aluminum or aluminum alloy by adding one, two or three appropriate reinforcements in suitable volume fractions. Worthy of note is the fact that aluminum (aluminum alloys) are associated with some disadvantages such as bonding, which is more challenging than in steel, low strength compared to steel and price is 200% more than steel, but with proper selection of reinforcement and heat treatment; strength can be increased to required level at a considerably reduced cost (Bhandare and Sonawane, 2013; Aigbodion *et al.*, 2010).

REINFORCING MATERIALS FOR HYBRID ALUMINUM MATRIX COMPOSITES (AMCs)

Reinforcements increase strength, stiffness, and temperature resistance capacity of aluminium matrix composites. Final properties of the composite depend largely on the properties of the reinforcement material selected and the processing route adopted. A few of these parameters are; reinforcement type, particle, size, shape, volume fraction, modulus of elasticity, and distribution in the matrix alloy (Singh and Chauhan, 2016; Surappa, 2003).

The different reinforcing materials that have been used in the development of stir cast aluminum matrix composites can be classified into three board groups: Synthetic ceramic particulates, industrial waste aggregates and agro waste derivatives (Bodunrin *et al.*, 2015).

Synthetic ceramic particulates are used as the reinforcements in the development of aluminium matrix composites, however high cost and limited supply of conventional ceramics reinforcing materials especially in developing countries has remain a major problem. Other challenges reported of interest in using ceramics particulate are inferior ductility, low fracture toughness and in ability to predict corrosion behavior (Pydi *et al.,* 2013; Macke *el al.*, 2012; Das *et al.*, 2014). Several approaches have been adopted to resolve these problems. One approach is finding alternative cheaper reinforcement which is aimed at providing solution to problem posed by high cost and limited availability of conventional ceramic particulates. Industrial waste aggregates and agro waste derivatives are some of the alternative reinforcing materials that have been investigated. Results obtained from the investigations carried out on these alternatives reinforcement have been promising as they show significant improvement in the properties of the composites developed over the unreinforced although. However, they possess inferior properties when compared to the aluminium matrix composites developed using synthetic ceramics particulates (Bodunrin *et al.*, 2015; Alaneme and Adewuyi, 2013).

Another approach involved development of aluminium matrix composites using two or more reinforcement materials known as hybrid composites. This approach gives room for possible reduction of cost coupled with property optimization. This has put hybrid reinforced aluminium composites under the spotlight as many researchers forecast the huge promise of developing high performance and low cost metal matrix composites through this route.

Thus, based on published articles studied, discussion on combination of reinforcements used in the synthesis of hybrid aluminum matrix composites is classified into three broad groups. These include hybrid aluminium composites reinforced with two synthetic ceramic particulates, hybrid aluminium composites reinforced with synthetic ceramic material combined with industrial waste and hybrid aluminium composites reinforced with synthetic ceramic material combined with agro waste derivative (Bodunrin *et al.*, 2015; Casati and Vedani, 2014; Devaraju *et al.*, 2013).

This review revolves around the works of various researches in the field of hybrid composites reinforced with two synthetic ceramic particulates, industrial waste combined with synthetic ceramic materials and agro waste derivatives combined with synthetic ceramic materials. Among the properties that have been investigated are: wear behavior, tensile strength, hardness, corrosion behavior and microstructure.

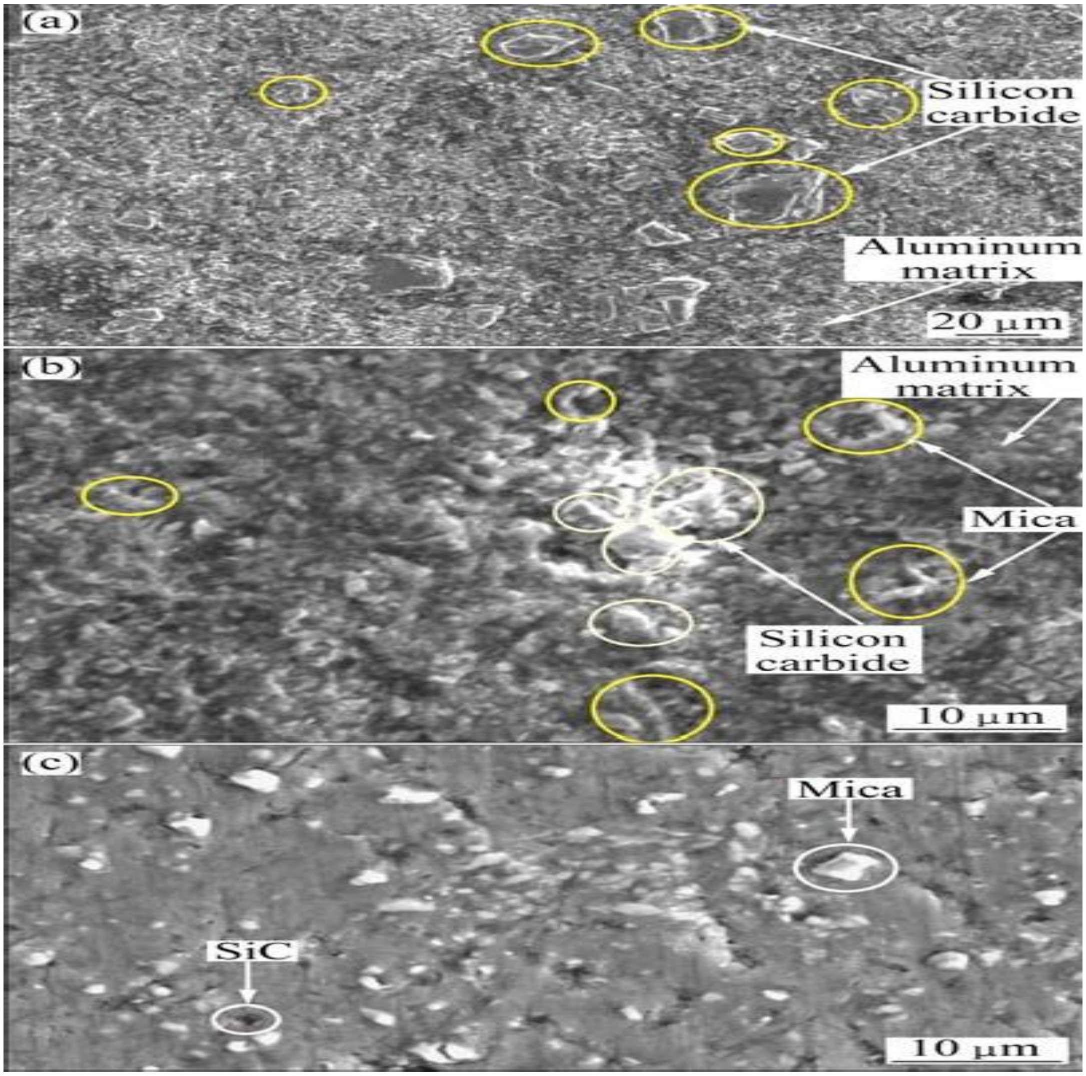

Figure 1. SEM images. (a)Al/10SiC composite. (b) Al/10SiC – 3Mica composite. (c) Al/10SiC – 6 Mica. (Rajmohan *et al*., 2013).

Hybrid AMCs reinforced with two synthetic ceramic materials

This category of hybrid AMCs are developed basically for performance optimization with less consideration on the production cost. Silicon Carbide (SiC), Alumina (Al_2O_3), Boron Carbides (B_4C), Tungsten Carbides (WC), Graphite (Gr), Carbon Nanotubes (CNT) and silica (SiO_2) are some of the synthetic ceramic particulate that has been studied but silicon carbide and alumina are mostly utilized compared to other synthetic reinforcing particulates (Bodunrin *et al*., 2015). Conventional aluminum matrix composites reinforced with SiC or Al_2O_3 have shown improved strength and specific stiffness over monolithic alloys but this occurs at the expense of ductility and fracture toughness (Alaneme and Adewuyi, 2013; Casati and Vedani, 2014).

Ductility and fracture toughness are important material properties that are necessary for preventing failures in service, stress or shock load applications. Also as mentioned earlier, corrosion performance of these aluminum matrix composites is not consistent judging from reports in the past. These have necessitated the use of two or more synthetic reinforcing particulates for property optimization. Graphite and Baron Carbide have been used alongside with SiC or Al_2O_3 to optimize the performance of AMCs (Devaraju *et al.*, 2013). Some of the findings in recent published articles are presented below.

Rajmohan *et al.* (2013) investigated the mechanical and wear properties of Al356 alloy reinforced Mica and SiC ceramic particulates fabricated through stir casting technique. Scanning electron microscopy (SEM) result (Figure 1) showed that the distribution of Mica and SiC particles was uniform which revealed the homogeneity of the cast composites. They further noted that homogeneous distribution of the reinforcements was essential

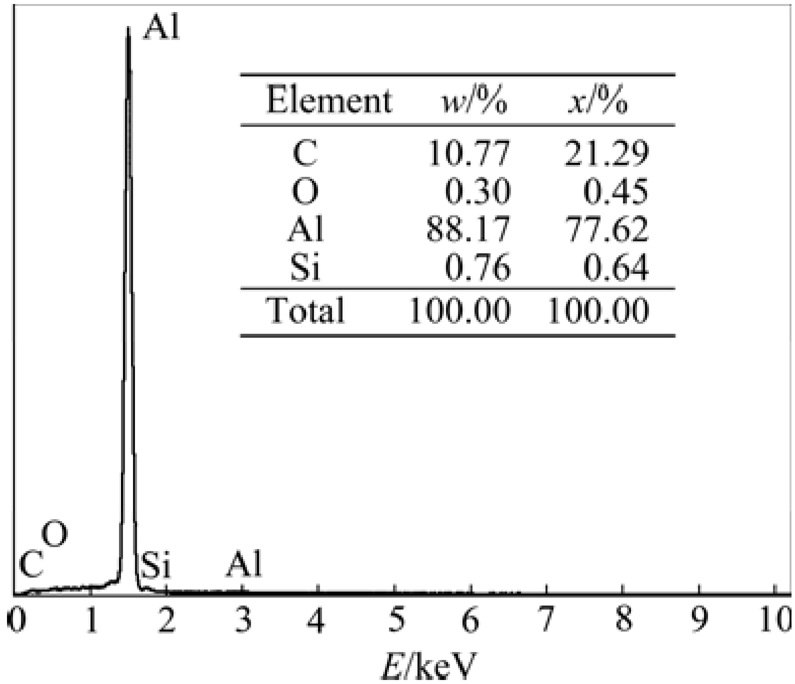

Figure 2. EDS spectrum of Al/10SiC – 3Mica composites.

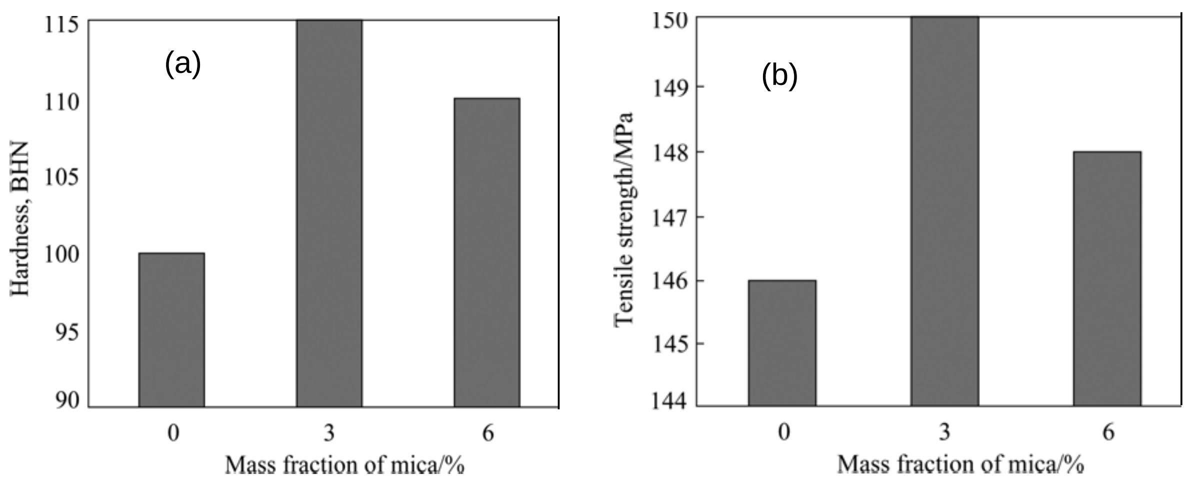

Figure 3. **(a)** Tensile strength (Mpa) **(b)** Hardness (BHN).

for the formation of a composite with uniform mechanical properties. Energy dispersive spectroscopy (EDS) analysis of Al10SiC3Mica reinforced composite (Figure 2) showed Al, O and C peaks which confirmed the presence of SiC and Mica within the composites.

Results of mechanical properties tests presented in Figures 3 and 4 showed that composite reinforced with 10 wt% SiC and 3 wt% Mica had the highest tensile strength of 150 Mpa while the hardness increased more or less linearly with the volume fraction of the particulates in the alloy matrix due to increasing phase of the matrix alloy.

Ramnath *et al.* (2014) evaluated the mechanical properties of aluminum hybrid composites reinforced with AL_2O_3 and B_4C. B_4C was considered despite its high cost because of its high strength, low density, extremely high hardness, good chemical stability and neutron absorption characteristics. The hybrid composites exhibited superior hardness and impact strength than unreinforced alloy. However, the unreinforced alloy had slightly higher tensile strength and superior flexural properties than the hybrid counterparts. Micro structural analysis revealed poor stirring and uneven distribution of the reinforcement in the

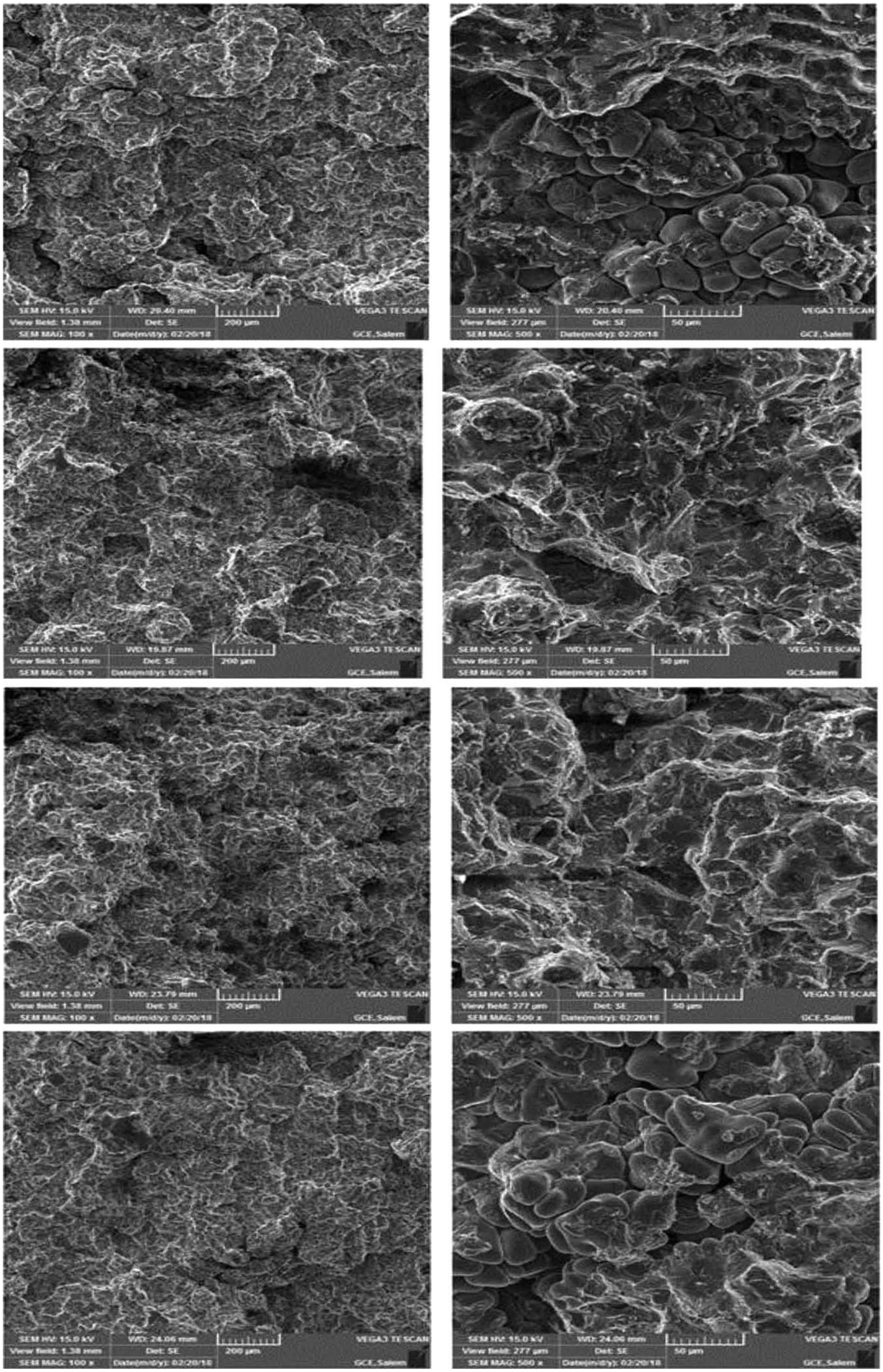

Figure 4. Fracture images of composites with different compositions (Pugalenthi *et al*., 2019).

matrix was responsible for the observation.

Pugalenthi *et al.* (2013) fabricated Al7075 composites with SiC and Al_2O_3 as reinforcements through stir casting method. Composition of the SiC particles were varied by 3, 5, 7 and 9 wt% and constant 2 wt% of Al_2O_3. Results of mechanical properties tests revealed an increase in tensile strength, yield strength and hardness as the volume fraction of the reinforcements increased. Fractographic study of the composites (Figure 3) showed that the increase in the weight percentages of the reinforcements changed the mode of failure from ductile to brittle to some extent which was clearly observed from dimples and deformed portions present near regions of the fracture.

Hybrid AMCs reinforced with synthetic ceramic and industrial waste

With an increase in population and industrialization, a lot of valuable natural resources are depleted to prepare and manufacture products. However, industrialization on the other hand has waste disposal issues causing pollution. Thus, industrial wastes have been used for further development of goods and products. Industrial wastes commonly used for the fabrication of aluminum metal matrix composites include Fly Ash, Red Mud and Wet Grinder Stone Dust (WSD) particles. Fly ash (FA) and Red mud are typical industrial waste gotten from the power plant and aluminum industry respectively while wet grinder stone dust is a bye product of quarries (Ravindran *et al.*, 2013; Anilkumar *et al.,* 2011).

These industrial wastes have been recommended to be appropriate for use as reinforcing materials in aluminum matrix composites. Despite the fact that research work reporting utilization of red mud and wet grinder stone dust as support in metal matrix composites are meager, broad studies have been done on utilization of fly ash as a fortification agent in both single and cross hybrid composites (Anilkumar *et al.,* 2011; Selvam *et al.*, 2013).

Fly ash is a bye product of coal combustion and is readily available in many industrialized nations such as USA, United Kingdom, Canada, and China among others. About 5 million tons of fly ash is produced in Canada annually. The oxides found in the FA include Al_2O_3, SiO_2 and Fe_2O_3 while other oxides that are present in trace amount include K_2O, NaO and MnO. The oxides make FA suitable for use in synthesis of aluminum matrix composites. Moreover, low density and low cost are often attractive benefits of fly ash.

Selvam *et al.* (2013) synthesized and characterized aluminum hybrid composites reinforced with SiC and fly ash via stir casting techniques. Tensile strength and hardness of the composites were improved due to high dislocation resulting from thermal mismatch between the reinforcement and the matrix in conjunction with large surface area of the hard ceramic phase, which bears the load transferred by the matrix when subjected to loading conditions. Micro structural evaluation revealed that SiC and fly ash was uniformly distributed in the aluminum matrix and fly ash was effective in suppressing the formation of Al_4C_3 phase due to presence of SiO_2 (Table 1) in the fly ash. Suppressing the formation of the Al_4C_3 phase by fly ash has been reported to improve the corrosion performance of aluminum hybrid composites.

Venkat Prasat and Subramanian (2013) studied the tribological properties of AlSi10Mg/fly ash/graphite hybrid metal matrix composite. They found that the tensile strength, hardness and wear resistance were higher in the hybrid composites compared to unreinforced alloy and alumina-graphite composites. The improved wear resistance was attributed to load bearing capacities of fly ash and the lubricating effect of graphite; wear rate was also observed to reduce with increase in fly ash content.

Natarajan *et al*. (2012) studied the dry sliding wear and mechanical behavior of Aluminum/Fly ash/Graphite hybrid metal matrix composites using Taguchi method and reported that load was the most influencing factor affecting the wear rate of the composites followed by sliding speed and fly ash content respectively. There was an increase in the hardness of the hybrid composites as fly ash content increases. Fly ash can also be used to suppress interfacial reaction that exists between matrix and the reinforcing particulate.

Hybrid AMCs reinforced with synthetic ceramic and agro waste derivative

A new generation of metal composites have been developed using agro–waste derivatives as reinforcement to aluminum matrix composites. The agro waste derivatives offer some advantages when used in the synthesis of aluminum matrix composites. These advantages include low cost, accessibility, low density and reduced environmental pollution. A few numbers of agro waste have been processed into ashes and their suitability for used as reinforcing phase material have been studied (Prasad and Krishna, 2011; Madakson *et al.*, 2012). Agro waste derivatives are believed to be very promising materials for the development of aluminum matrix composites on a commercial scale. This is because there are limited synthetic ceramic reinforcing materials in most developing countries and where these are available, they are often very expensive. Similarly, most developing countries are not as industrialized as the developed countries, so the use of industrial waste is quite scarce as these wastes are limited. Madakson *et al*. (2012) characterized coconut shell ash for potential utilization in metal matrix composites for automotive applications. They dealt with the characteristics of coconut shell ash using spectroscopic analysis, density measurement, particle sizes and refractoriness. The results were compared and it was observed that the ash possessed nearly same chemical phases and other functional groups as

Table 1. Chemical composition of fly ash (Selvam *et al.,* 2013).

Elements	SiO_2	Al_2O_3	MnO	Na_2O	K_2O	CaO	Fe_2O_3	TiO_2	Others
Wt %	49.5	25.54	1.03	0.47	0.65	3.13	8.92	0.53	2.15

Table 2. Mechanical properties of matrix and hybrid composites (Prasad *et al.*, 2014).

S/N	Sample	Hardness BHN	YS MPa	UTS MPa	% elongation
1	A356.2 alloy	68	168	263	7.35
2	A356.2/2%RHA/2%SiC hybrid composite	74	182	296	6.25
3	A356.2/4%RHA/4%SiC hybrid composite	83	196	310	5.60
4	A356.2/6%RHA/6%SiC hybrid composite	96	230	333	5.15
5	A356.2/8%RHA/8%SiC hybrid composite	104	258	356	4.9

reinforcements like fly ash, rice husk ash and bagasse that have been used in metal matrix composites specifically for automobile applications.

Subramanian *et al*. (2019) carried out investigations on tribo–mechanical behavior of Al- Si10- Mg/Sugarcane bagasse ash/SiC hybrid composites. Morphological analysis was done using scanning electron microscopy to ensure the distribution of the reinforcement particles in the matrix alloy. Worn surfaces of the wear tested specimens and fracture morphology structure of tensile tested specimens were analyzed. Results showed that the composites reinforced with sugarcane bagasse ash and silicon carbide exhibited superior wear resistance.

Agricultural waste derivatives as reinforcement material in aluminum matrix composites include: Bamboo Leaf Ash (BLA), Rice Husk Ash (RHA), Bagasse Ash (BA), Palm Kernel Shell Ash (PKSA), Maize Stalk Ash (MSA), Corn Cob Ash (CCA), Bean Shell Waste Ash (BSWA) just to mention a few (Loh *et al*, 2013; Alaneme *et al.*, 2013; Aigbodion *et al.*, 2010; Prasad and Krishna, 2011; Madakson *et al.*, 2012).

In general, the agro waste derivatives improved the properties of the aluminum matrix composites over the unreinforced alloy. Results obtained from the investigations carried out on these alternative reinforcements have been promising as they show significant improvement in the properties of the composites developed over the unreinforced alloy. However, the properties obtained are inferior when compared to those offered by aluminum matrix composites developed using conventional synthetic ceramic reinforcements. Research efforts seeking to produce high performance aluminum matrix composites where strength levels are maintained at reduced cost informed the addition of agro waste derivative as a complimenting reinforcement for the fabrication of this class of hybrid aluminum metal matrix composites (Bodunrin *et al*., 2015).

An overview of the recent studies on aluminum metal matrix composites reinforced with agricultural waste derivatives and synthetic ceramic particulates is presented below:

Prasad *et al.* (2014) carried out an investigation on stir cast aluminum hybrid composite containing equal amount of rice husk ash and silicon carbide from 2 to 8% in step of 2. They found out that there was homogenous distribution of the reinforcement in the matrix. Hardness, yield strength and ultimate tensile strength increased with increase in the reinforcement as shown in Table 2.

The strengthening mechanism was attributed to thermal mismatch between the matrix and reinforcements which generated increasing dislocation density as the reinforcing materials increased. Furthermore, the ageing response of the hybrid composites at 155°C was faster than the monolithic alloy. The time taken to obtain maximum hardness for the hybrid composites was higher than that of the monolithic alloy due to higher dislocation density of the composites.

Alaneme and Adewale (2013) evaluated the mechanical behavior of Al (6063) hybrid composites reinforced with 5, 7.5 and 10 wt% silicon carbide and RHA. The mix ratios of the RHA in the reinforcing phase are 1:0; 1:3; 1:1; 3:1 and 0:1. It was reported that the tensile strength, yields strength and specific strength of the of the composites increased with increasing weight percent reinforcing phase (RHA+SiC) while the fracture toughness decreased with increasing weight percent of the reinforcing phase. The percentage elongations of the composites were invariant of the reinforcing phase and the RHA content and as a result, the authors acclaimed that the addition of the RHA did not have a negative influence on the ductility of the composites. The increase in strength was ascribed to similar mechanism stated by Prasad *el al.* (2014). The authors also revealed that a careful observation of the role of RHA on the mechanical properties of the composites shows that yield strength, ultimate tensile strength and specific strength reduces as the content of RHA in the reinforcing phase increases. This was attributed to the lower hardness and elastic modulus of silica present in the RHA as compared with the hardness of the silicon carbide. Despite the reduction in strength, the percentage reduction of the specific strength was quite low when compared with yield strength and ultimate tensile strength. Also, sample with reinforcement mix ratio of 1:3 (RHA:SiC) was reported to have very close values to that of the singe reinforced Al-Mg-Si/SiC composites. The hybrid composites containing RHA had improved fracture toughness due to reduction in hard SiC particulate in the composites.

Alaneme and Adewuyi (2013) investigated the influence of Bamboo Leaf Ash (BLA) as a complementing reinforcement to Al_2O_3 on the mechanical behavior of Al-Mg-Si based hybrid composite. BLA constituted 2, 4 and 6 percent of the entire 10 wt% of the reinforcing phase. It was reported that the tensile strength, yield strength and specific strength reduced with increasing BLA in the reinforcing phase. However, the slight reduction was less than 9% even with 40% replacement of Al_2O_3 by BLA. This indicates that the introduction of the BLA does not have significant effect on the performance of the hybrid composites. The BLA mix ratios as reported in this case when compared to the case of RHA exhibited improved ductility and resistance to brittle fracture when used as a completing reinforcement to synthetic reinforcement (Al_2O_3 and SiC). Similar findings have been reported on the tensile strength, specific strength, yield strength and fracture toughness of aluminum hybrid composites containing SiC and BLA. The only exception in this case was an increased ductility as the content of BLA increases in 10% weight of the reinforcing phase.

Considering the articles surveyed on hybrid aluminum matrix composites, it is reasonable to conclude that using agro waste derivatives as a complementing reinforcement in the development of hybrid aluminum matrix composites can improve the fracture toughness and ductility of these composites without significant drop in strength.

Despite the potentials of agro waste derivatives in cost reduction and maintaining performance levels in terms of mechanical properties, a few numbers of researchers were curious about the influence of agro waste derivatives reinforcement on the corrosion and wear performance of hybrid AMCs when they are used in applications where they are exposed to corrosive and wear attacks. The agro waste derivatives are known to have the potentials of suppressing Al_2O_3 phase due to presence of more than 50% Silica in their composition just as in the case of fly ash. It was of interest to some researchers to find out if this phenomenon would help achieve improved corrosion resistance in hybrid AMCs reinforced with synthetic and agro waste derivatives reinforcements.

CONCLUSION

The following conclusions are drawn from the review:

1. Aluminium matrix hybrid composites can be successfully synthesized by the stir casting and powder metallurgy methods which can be utilized even at commercial scales.
2. Aluminium hybrid composites exhibit superior hardness, wear resistance and impact strength than the unreinforced alloy and the single reinforced composites. It was also observed that the mechanical and tribological properties increased with increasing reinforcements.
3. For the new generation of hybrid aluminium composites, which use agro and industrial waste derivatives, improved performance in comparison with the unreinforced alloy and single reinforced composites have, being established at a reduced production cost. More agro and industrial waste derivatives should be investigated and further research should be concentrated on how to optimize the production process in order to determine the optimum process parameters.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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