INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue VII, July 2024

Physico-Chemical and Microstructural Analysis of Al-Mg-Si Alloy Matrix Composites Reinforced Groundnut Shell ash Particulates

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DOI: https://doi.org/10.51583/IJLTEMAS.2024.130718

Received: 18 July 2024; Accepted: 06 August 2024; Published: 20 August 2024

Abstract

Metal matrix composites are an appealing alternative to monolithic metals for a variety of technical applications due to their superior mechanical and physical properties throughout a broad range of operating conditions. In the current study, different weight percentages of 150 µm groundnut shell ash (GNSA) particles (2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 25% and 30%) were used to reinforce Al-Mg-Si alloy. Stir-casting was used to prepare the composite in a permanent mild steel mould. A number of the composites' physical, chemical, and microstructural characteristics (density, percentage porosity, XRF and SEM-EDS) were assessed, compared, and analysed with those of the matrix alloy. Oxides that could enhance the composites' mechanical, physical, and structural qualities were found during the structural assessment evaluation of the reinforcement. The microstructural analysis demonstrated that the GNSA reinforcements' secondary phase was uniformly distributed throughout the primary phase of the Al-Mg-Si alloy matrix. The added GNSA particles decreased the produced composite's density below that of the base alloy, and the percentage porosity of the composites rose as the groundnut shell ash content increased and remained within the upper limit allowed for cast aluminium metal matrix composites. The composites that were created showed evidence of intermetallic compound formation.

Keywords - Al-Mg-Si, Groundnut shell ash, AA6061 matrix composite, Percent porosity, Microstructural.

I. Introduction

Aluminium is the most widely used metal after steel because of its versatility. Stronger, lighter, and less expensive materials are required for engineering applications. Some of the property combinations that distinguish aluminium 6061 metal matrix composites include high specific strength, a low coefficient of thermal expansion, high thermal resistance, good damping capacities, superior wear resistance, high specific stiffness, and acceptable corrosion resistance [1]-[9]. Metal matrix composites (MMCs) are rapidly replacing traditional monolithic metallic alloys in a wide range of industries, including aerospace, automotive, and defence [1], [10]-[14]. The high expense of using standard reinforcements such as silica (SiO_2), tungsten (W), calcium oxide (CaO), aluminium oxide (Al_2O_3), silicon carbide (SiC), titanium carbide (TiC), and so on limits the applications for aluminium metal matrix composites (AMMCs) [6], [11]. As a result of current industrial advances, aluminium alloy composites are becoming increasingly essential in engineering applications. Because of its ability to improve the many properties of the composite material, the use of agricultural waste ash in reinforcement—such as groundnut shell ash (GNSA), rice husk ash (RHA), palm kernel shell ash (PKSA), corn cob ash (CCA), coconut shell ash (CSA), bamboo leaf ash (BLA), etc.—is becoming increasingly important [15]-[20]. The quantity of waste generated by industrial, mining, and agricultural processes has expanded dramatically as a result of worldwide population growth and growing living standards caused by technological improvements. The amount of waste produced is beginning to concern environmentalists and citizens worldwide [21], [22]. Aluminium matrix composites (AMCs) are now manufactured utilising a variety of traditional and unique processes. The processing technique determines the properties of AMCs. Although a liquid process, such as casting, is simpler and less expensive, its use is limited due to the reinforcement's low wettability in molten aluminium. Stir casting is the preferred method for manufacturing aluminium metal matrix composites due to its cost-effectiveness, simplicity, and ability to make large and complicated parts [3], [23]-[25]. Using waste materials could reduce environmental contamination, and recycling waste materials by converting them into valuable resources for the automotive, aerospace, and construction industries could keep natural disasters from occurring [11], [26]-[29]. It has been discovered that agricultural waste ashes contain high concentrations of refractory minerals that can be used to make composites, such as alumina (Al_2O_3), silica (SiO_2), hematite (Fe_2O_3), carbonate ($CaCO_3$), and calcium (Ca).

II. Materials and Methods

A. Materials

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The materials used was Al-Mg-Si alloy as the matrix material which was obtained from Alna Aluminium Inc., China. Groundnut shell ash (GNSA) particulate as the reinforcement material which was obtained from Ogwashi-Uku, located at a longitude: of 6°10'41" N and latitude: 6°31'28" E, Delta State, Nigeria

B. Experimental Methods

1) Collection and preparation of groundnut shell:

The gathered groundnut shells were cleansed with warm water, sun-dried for two weeks, and then processed into a fine powder in the Ogwashi-Uku market using a locally fabricated grain (wheat, corn, beans, etc.) grinding machine. 1000 g of pulverised groundnut shell powder was put in stages into a muffle furnace and ashed at 500 °C for one hour [11], [30]. The temperature and duration utilised for ashing were determined after multiple attempts and are intended to allow for complete ash production while maintaining a single-phase material. The optimal ashing was virtually observed at 500 °C for one hour. The ashing was conducted at 450 °C, 500 °C, 550 °C, and 600 °C for 45 minutes, one hour, one hour 15 minutes, and one hour 30 minutes [30]. The powdered groundnut shell ash is displayed in Fig. 1(a).

Fig. 1. (a) Groundnut shell ash powder

2) Groundnut shell ash particle size analysis:

Groundnut shell ash particles size analysis was carried out at the Delta State Polytechnic, Ogwashi-Uku's Metallurgical Engineering Laboratory. For complete categorisation, 1000 g GNSA was placed in a sequence of decreasing fineness sieves and shaken for 15 min [11]. Material retained below the 150 µm sieve was used in this study as GNSA particles.

3) Stir casting:

The metal matrix composite was fabricated in metallurgical engineering laboratory of Delta State Polytechnic, Ogwashi-Uku using stir casting method. The sample was prepared by varying the weight percentage of reinforcing material (Groundnut Shell Ash) particles at an interval of 2.5 wt % from 0 to 30 wt % with, remaining balance being Al-Mg-Si alloy matrix. It means splitting the matrix into different PKSA weights. The aluminium alloy was melted in a stainless steel melting pot that had been pre-heated by a muffle furnace. The furnace was heated to ± 700 °C for three hours. The GNSA particles were heat treated in an oven at 50 °C for three hours to promote wettability and temperature equalization before they were charged into the molten aluminium. The alloy was fully melted in the furnace by increasing the temperature to 750 °C, then cooled to 600 °C to preserve a semi-solid state. At this step, the preheated particles of groundnut shell ash were added and manually stirred using a steel stirring rod in accordance with [31]-[32]. The composite slurry was manually mixed, then heated to 750 °C in the furnace before being put into a 200 mm long by 16 mm diameter permanent cylindrical mould that had been preheated [30, 32]. Fig. 1. (b) and (c) display the representative cast composites and mild steel permanent mould respectively.

Fig. 1. (b) As-cast AA6063/GNSA composites, (c) Fabricated permanent mould

4) Determination of density of produced composites:

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The cleaned Al-Mg-Si/GNSA composite samples were carefully weighed on an electrical scale before being submerged in water. The weight of the sample in water was determined, and the sample's volume was computed using the Archimedes principle, which takes into account the effect of water displacement. Eq. (1)'s expression was used to calculate the experimental density, and the experimental density of the composite was tabulated (Table 1).

$$Density = \frac{Mass(M)}{volume(V)} \qquad \text{Eq. (1)}$$

5) Determination of percentage porosity of produced composites:

Using an electrical scale, the measured weight of a test sample was divided by its measured volume to determine the experimental density of each grade of composite produced. The percentage porosity of the composites was evaluated by comparing the experimental and theoretical densities for each composition of the composites formed (Table 2). The percent porosity was calculated using the relation (Eq. (2)) [11], [30].

$$percentage\ porosity = \left(\frac{\rho^{T} - \rho^{EX}}{\rho^{T}}\right) * \frac{100}{1} \qquad \text{Eq. (2)}$$

Where ρ^{T} = Theoritical density and ρ^{EX} = Experimental density.

6) Chemical analysis of groundnut shell ash particulate:

XRF technique was used to examine the chemical composition of the groundnut shell ash particle (reinforcement). An energy dispersive x-ray fluorescence (EDXRF) spectrometer type known as "Minipal 4" was used in this experiment to determine the reinforcement's oxide levels, both quantitatively and qualitatively. XRF identifies elements between sodium (Na, Z = 11) to uranium (U, Z = 92) with excellent resolution and fast analysis.

7) Microstructural evaluation of the produced composites:

Using a JSM 7600F Jeol ultra-high resolution field emission gun scanning electron microscope (FEG-SEM) equipped with an EDS, the microstructural properties and qualitative element composition of the composites were fully investigated.

III. Results and Discussion

A. Density

The results of the density measurement of Al-Mg-Si with varying weight percentage additions of GNSA are shown in Table 1. The result shows that as groundnut shell ash addition to the matrix increases, the density of the Al-Mg-Si/GNSA reinforced alloy decreases. The research findings from [11] were consistent with this pattern. The density of the Al-Mg-Si/GNSA reinforced composites was 2.62 g/cm^3 when 2.5 weight percent of GNSA was added; however, at 30 weight percent, it decreased to 2.04 g/cm^3. This is due to the fact that GNSA particles are less dense than those of aluminium alloy, and studies have indicated that employing GNSA to create lightweight composites suitable for automotive applications may result in energy savings.

Table 1: Experimental density of Al-Mg-Si/GNSA composite

Compositions of GNSA (%)	Experimental density (g/cm3)
0	2.68
2.5	2.62
5	2.57
7.5	2.52
10	2.47
12.5	2.42
15	2.37
17.5	2.32
20	2.27
25	2.15
30	2.04

B. Percentage Porosity

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The porosity of the final composites provides an explanation for the difference between the experimental and theoretical densities divided by the theoretical densities of the composites. Porosity was shown to increase with the number of GNSA particles that served as reinforcement. The porosity level is caused by either trapped air or low wettability of the reinforcement [33]. High porosity leads to poor strength and mechanical properties [33]. The results showed that the apparent porosity values of the composites increased slightly as the weight percentage of GNSA added increased as illustrates in Table 2. The porosity of the reinforced composite was 1.14% at 2.5 weight percent of GNSA addition and 2.86% at 30 weight percent of GNSA addition. The value of the reinforcement raises the proportion of pores and voids in the AMMC. But the percentage porosity of every composite that was produced was less than the maximum permitted for cast metal matrix composites [11], [32]-[34].

Table 2: Percent porosity of Al-Mg-Si/GNSA composite

Compositions of GNSA (%)	Theoretical density (g/cm3)	Experimental density (g/cm3)	Porosity (%)
0	2.70	2.68	0.74
2.5	2.65	2.62	1.14
5	2.60	2.57	1.16
7.5	2.55	2.52	1.19
10	2.50	2.47	1.21
12.5	2.45	2.42	1.24
15	2.40	2.37	1.27
17.5	2.35	2.32	1.30
20	2.30	2.27	1.33
25	2.20	2.15	2.27
30	2.10	2.04	2.86

C. Chemical Analysis

1) X-ray fluorescent spectrophotometer (XRF) results of groundnut shell ash (GNSA):

Table 3 shows the chemical composition of the GNSA (in oxide form) based on XRF analysis. According to Table 3, the concentrations of SiO_2, Fe_2O_3, Al_2O_3, P_2O_5, and K_2O appear to be higher in the following oxides. Increased levels of phosphorus, silica, alumina, and other oxides were verified by [6], [15], [31]. Because groundnut shells include hard components including SiO_2, Al_2O_3, Fe_2O_3, and K_2O, they can be used as particle reinforcement in metal matrices composites. As a result, the study's findings suggest that employing GNSA as a particle reinforcement in the creation of metal matrix composites is feasible. Due to their similar chemical composition, the XRF results are compatible with different particle organic and agricultural waste reinforcements used in matrix composites, such as rice husk ash, coconut shell, periwinkle shell, and bagasse ash [11], [28], [33]. Fig. 2 shows the elemental composition of the GNSA particles. The elements that are present in the sample (GNSA) could be determined using peak search or peak match. A mathematical method called peak search is used to locate the peaks in a spectrum. Peak match can also determines the elements to which the peak profiles belong. This analysis made use of peak match Fig. 2. The positions of the peaks are compared to a database containing the positions of every feasible line to achieve this [35].

Table 3: XRF oxide analysis of the groundnut shell ash (GNSA)

Compound (Oxide)	Conc. (%)
SiO_2	49.91
Al_2O_3	8.97
Fe_2O_3	8.94
MgO	3.68
P_2O_5	2.41
Na_2O	2.02
TiO_2	0.23

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue VII, July 2024

MnO	0.14
CaO	6.04
K_2O	8.11
CuO	0.07
ZnO	0.04
Ni_2O	0.004
Cl	5.45
SrO	0.61
Others	≤0.28
LOI	3.32

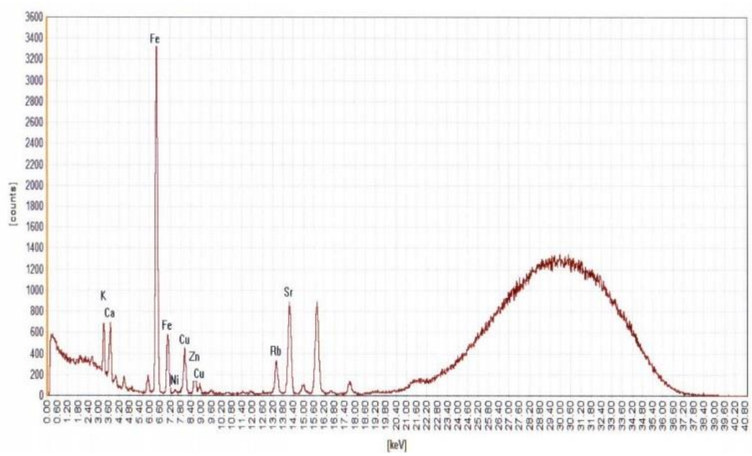

Fig. 2 XRF spectra showing the elemental composition of the groundnut shell ash (GNSA) particles.

D. Microstructural examination

Fig. 3 displays representative morphological properties of the unreinforced Al-Mg-Si alloy (0 weight percent GNSA). Fig. 3 vividly shows a variety of needle-like features which were also observed by [36]. Since Mg promotes the liquid-vapour surface tension and Si especially acts on the contact angle, these elements are crucial to the infiltration of GNSA preforms because they affect the aluminium alloy's wetting behaviour [36].

However, the inclusion of GNSA particles in the composite containing 10 weight percent GNSA particles results in toughening mechanisms (Fig. 4). The morphology showed that the secondary phase of the GNSA reinforcements was evenly dispersed throughout the aluminium matrix's main phase. The EDS result of the unreinforced alloy (0 weight percent GNSA) contained the elements Al, Mg, Si, C, Fe, Cr, Mn, O, and Cu, while the matrix composite Al-Mg-Si reinforced with 10 weight percent GNSA particles had the elements Al, Mg, Si, C, Fe, C, O, and Cu (Fig 3). The alloy's microstructural study reveals the existence of Mg_2Si and AlFeSiMn as intermetallic phases in addition to an intermetallic grain. The needle-shaped AlFeSiMn intermetallic was found by the SEM and EDS investigations. Further studies by [36], indicate that the presence of Fe and Mn impurities in aluminium causes the intermetallic phase to develop.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue VII, July 2024

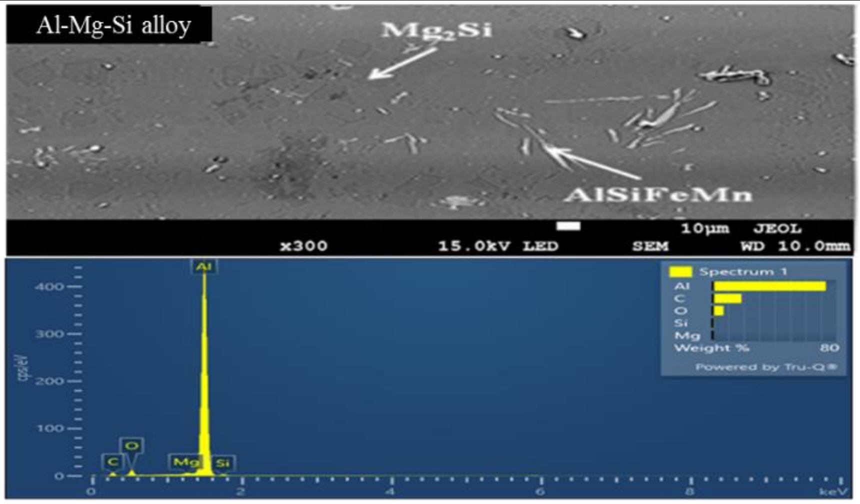

Fig. 3 SEM-EDS micrograph of Al-Mg-Si alloy as-cast

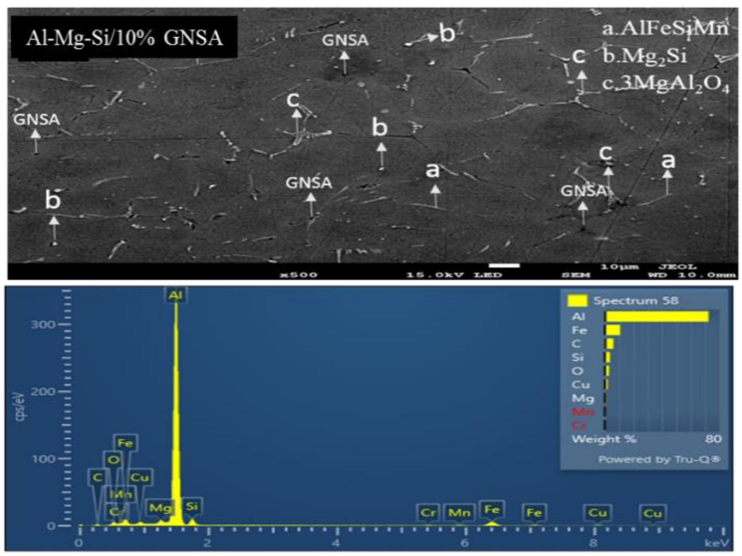

Fig. 4 SEM-EDS micrograph of Al-Mg-Si/10%GNSA

IV. Conclusion

Drawing from the results, one may deduce the following:

To make the Al-Mg-Si/GNSA composites, double stir casting was employed. GNSA can be used as a reinforcement material while creating AMMCs because of its strong oxides. The density of Al-Mg-Si/GNSA composites decreased with an increase in groundnut shell ash content. This implies that the creation of lightweight metal composites may benefit from the use of groundnut shell ash particles as reinforcement. Al-Mg-Si aluminium alloy can be infused with groundnut shell ash particles to create lightweight, low-cost aluminium composites with improved structural and physico-mechanical properties.

Declaration of Competing Interest

In terms of potential competing interests, the following financial and interpersonal relationships are declared by the authors: According to Elvis Emifoniye, the Tertiary Education Trust Fund provided the financial support.

Acknowledgement

The Tertiary Education Trust Fund (TET Fund), Nigeria, is acknowledged by the authors for providing financial support for this study via the Institution Based Research (IBR) Interventions programme.

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