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Research article

Mechanical and microstructural characteristics of recycled aluminium matrix reinforced with rice husk ash

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Abstract: This study used rice husk ash to reinforce recycled aluminium waste cans matrix through stir casting technique to produce a composite. The rice husk ash was added to the aluminium matrix in 0, 5, 10, 15, and 20 wt%. Mechanical and microstructural analyses were carried out on the composites. The tensile strength of the composite increases at 5 wt% addition of reinforcement and increases further to reach a maximum of 121.6 MPa at 10 wt% addition. The tensile value then dropped at 15 wt% and reduced further at the 20 wt% particulate addition. A similar trend was observed for the impact strength with the maximum value of 81.5 J occurring at 10 wt% addition before declining at the higher percentages of reinforcement. The hardness of the composites continues to increase as the percentage of the rice husk addition rises leading to the highest Brinell hardness number (BHN) of 74.5 occurring at the highest percentage of rice husk ash addition. The density of the composites decreases as the wt% addition of the reinforcement increases giving the lowest density value of 2.46 g/cm^3 at 20 wt% addition. The microstructures exhibited uniformity in the dispersion of the reinforcement into the aluminium matrix, although little particulate agglomeration could be noticed at higher percentages of rice husk addition. This study provides a significant boost to the attainment of lightweight materials in the automobile and other allied industries. The improvement in the mechanical properties and the lower density of the composites attained in this study are vital factors considered in material selection and design for lightweight engineering applications.

Keywords: rice husk ash; aluminium cans; composite; microstructure; mechanical properties

1. Introduction

Composites are formed when two or more materials that are insoluble in one another are combined on a macroscopic scale. One of the materials is known as the reinforcing phase and the other material in which it is embedded is known as the matrix phase [1–3]. The composite's reinforcing phase usually comes in the form of flakes, particles, and fibre and is harder than the matrix phase. The matrix phase of the composite materials is generally continuous in nature and is characterized by ductility. The development of composites is gaining wide attention in engineering today due to their unique properties where the constituent elements compensate for each other weaknesses thereby imparting good mechanical, corrosion, thermal and electrical conductivity, and other properties to the composites. Aluminium alloy remains one of the versatile metals that have found wide applications in engineering due to its malleability, ductility, high strength-to-weight ratio, durability, and corrosion resistance ability [4,5]. Aluminium matrix composites (AMC) have attracted the attention of many researchers. The idea of reinforcing aluminium is to increase the tensile strength, hardness, toughness, wear resistance, corrosion, and other properties for application to areas where lightweight with great ductility, strength, toughness, high wear, corrosion resistance, and low-cost materials for industrial applications are required [6]. One group of reinforcements that have been successfully applied to aluminium matrix is the agricultural wastes [7–10] These wastes include wood, coconut shells, bagasse, melon shells, groundnut shells, palm kernel shells, rice husks, and other plant wastes. [11–14]. Many researchers' attention has been drawn particularly to the potential of rice husk ash as reinforcement on metal matrix and concrete [15–17]. Studies have shown that every 1000 kg of milled rice produces about 220 kg of husk. An estimated 70 million tons of rice husks are generated annually globally [18]. This rice husk often causes pollution to the land and the surrounding environment if improper disposal occurs. Burning is a common method of disposal of rice husks which contaminates the atmosphere. The gases from the burning could severely affect health, leading to respiratory diseases such as asthma, chronic bronchitis, emphysema, and decreased lung function. The black soot generated during the burning causes poor visibility which could result in road accidents [12]. The challenges of rice husk disposal and the health risks involved explain why the attention of researchers is drawn to its utilization for various engineering purposes. Several authors have attempted to use rice husk and its ash to reinforce some metal matrix to form composites. Saravana and Kumar [19] studied the mechanical behaviour of AlSi10Mg reinforced with rice husk ash. They reported enhancement in the mechanical characteristics of the composites. Priyank and Amit [12] reviewed some works on aluminium matrix reinforced with rice husk ash. They reported that the mechanical behaviour of the metal matrix composites was enhanced by including rice husk ash nanoparticles in smaller quantities. Seikh et al. [20] also reported a trend in improved hardness and wear resistance of rice ash-reinforced aluminium matrix composites. Darekar et al. [21] employed synthesized rice husk ash to reinforce epoxy for applications in microelectronics. Their study revealed a significant improvement in the microhardness and storage modulus of the rice husk ash/epoxy composites. Prapata et al. [22] reinforced 6061 aluminium alloys with rice husk ash and found that the composites exhibit 15% higher wear resistance than the pure aluminium. Vasamsetti et al. [23] used the Taguchi optimization technique to study the effect of stirring time and speed on the mechanical properties of rice husk reinforced Al6061 aluminium alloys and reported that the 2 wt% of rice husk ash addition gave the highest hardness; however, the two factors investigated have no significant effects on the hardness of the produced composites. Siva and Rama [24] also reinforced A3562 with rice husk ash with 2, 4, 6, and 8 wt%. They reported an improvement in the composite's tensile and hardness values for all the weight additions. The above literature generally revealed the potential of rice husk ash as an enhancer of mechanical properties when added to a metal matrix in the right quantity. Aluminium cans have gained wide uses as a container for packaging food and drinks. However, the disposal of the cans after consumption of the contents has become a challenge as well as the wastes generated from crops known as agricultural wastes. Common disposal methods such as burning or burying these wastes constitute health hazards to man and the environment. This study harnesses these two wastes to develop a composite to reduce the environmental hazards their improper disposal poses and further explore their capabilities as composites for lightweight engineering applications. This work successfully utilized rice husk as the reinforcement on recycled waste aluminium cans matrix to produce aluminium rice husk ash composites.

2. Materials and methods

2.1. Waste cans preparation

The aluminium waste cans were obtained at various dumping sites in Kabba, Kogi state, Nigeria, and crushed manually (Figure 1). The elemental analysis done on the aluminium alloy is presented in Table 1.

Table 1. Aluminium waste cans chemical composition (wt%).

Element	Fe	Mn	Ti	K	Si	Cu	Zn	Mg	Cr	Al	Others
wt%	0.431	0.388	0.006	0.013	0.59	0.074	0.194	2.143	0.008	96.043	0.11

Figure 1. Waste aluminium cans.

2.2. Rice husk ash production

The rice husks (Figure 2) were obtained from a local source in Nigeria. They were thoroughly washed, dried in the sun, and then burnt in a ceramic container. During this time, the rice husk became carbonized from the scorching of the organic matter. It was then placed in the furnace and heated to 600 °C for 10 h. The produced ashes were then sieved with a 38 µm sieve size to obtain the reinforcement (Figure 3).

Figure 2. Rice husk.

Figure 3. Rice husk ash.

2.3. Analysis of the produced rice husk ash

X-ray fluorescent (XRF) machine (Thermo Fisher ARL PERFORM'X Sequential XRF) was utilized for the compositional analysis of the rice husk ash as presented in Table 2.

Table 2. Rice husk ash composition.

Oxides	wt%
Silica (SiO_2)	75.81
Aluminium oxide (Al_2O_3)	0.8
Sodium oxide (Na_2O)	1.58
Magnesium oxide (MgO)	3.74
Potassium oxide (K_2O)	2.52
Calcium oxide	1.39
Manganese oxide (MnO)	0.01
Titanium oxide (TiO_2)	0.050
Phosphorous oxide (P_2O_5)	11.29
Haematite (Fe_2O_3)	0.87
Titanium oxide (TiO)	0.03
Sulphur (S)	0.56
Chlorine (Cl)	0.23
Zinc oxide (ZnO)	0.05
Copper Oxide (CuO)	0.01
ZrO_2	0.01
Barium Oxide (BaO)	0.11
Thorium (ThO_2)	0.01
Nobium (Nb_2O_5)	0.01

2.4. Composite production

The furnace was heated to 500 ℃ and the manually crushed aluminium waste cans were trusted into the furnace in a crucible made of mild steel. The temperature of the furnace was then raised to 800 ℃ since the melting point of aluminium is about 660 ℃. The charge waste cans were left in the furnace for about 45 min and stirred to achieve complete melting. The crucible containing the molten aluminium was let out of the furnace and the floating slag and other impurities were separated from the molten metal. After that, the rice husk ash as the reinforcement was introduced into the molten aluminium in percentage by weight and stirred vigorously for one minute. The mixture was transferred back to the furnace and held for about 15 min, stirring it again and gently pouring it into the prepared sand mould Figure 4. The composites in the mould were left to cool at room temperature for 24 h before being knocked out of the mould (Figure 5) and taken for machining into the various standards required for the mechanical testings.

Figure 4. Sand mould with the composites.

Figure 5. The composites before machining.

2.5. Mechanical properties testing

The tensile samples were prepared following the B557M ASTM standard [25]. Three samples were tested for each wt% addition using the Instron universal testing machine and the average was evaluated. The Brinell hardness on the other hand was carried out using ASTM E10-18 2017 [26] with a universal testing machine incorporated with a diamond ball indenter. A load of 300 kgf was applied for 15 s, five indentations were made on each sample, and the average was evaluated. Two samples each cut according to the ASTM standard E23 of the year 2007 [27] were tested for impact toughness on each composite using the Avery-Denison Universal Impact-Testing Machine.

2.6. Density

The density of the unreinforced aluminium and those of the composites were evaluated using Archimedes' principles. The densities were evaluated using the conventional formula given in Eq 1 [28].

$$\rho c = \left(\frac{Wc}{Wc - Ww}\right) \times \rho w \quad (1)$$

where ρ is the density, W is the measured weight, and the subscripts c and w refer to the composites and water, respectively.

2.7. Surface morphology examination

Samples of about 10 mm were cut from each composite rod for surface examination. The samples were mounted, grinded, polished to mirror surfaces, and then etched using Weck's reagent. The composites' microstructures were examined with an optical microscope set at a magnification of 50×. Scanning electron microscope (SEM) and electron dispersion spectroscopy (EDS) analysis were carried out on three samples including the control sample. The samples were selected based on their mechanical performance.

3. Results and discussion

3.1. Tensile

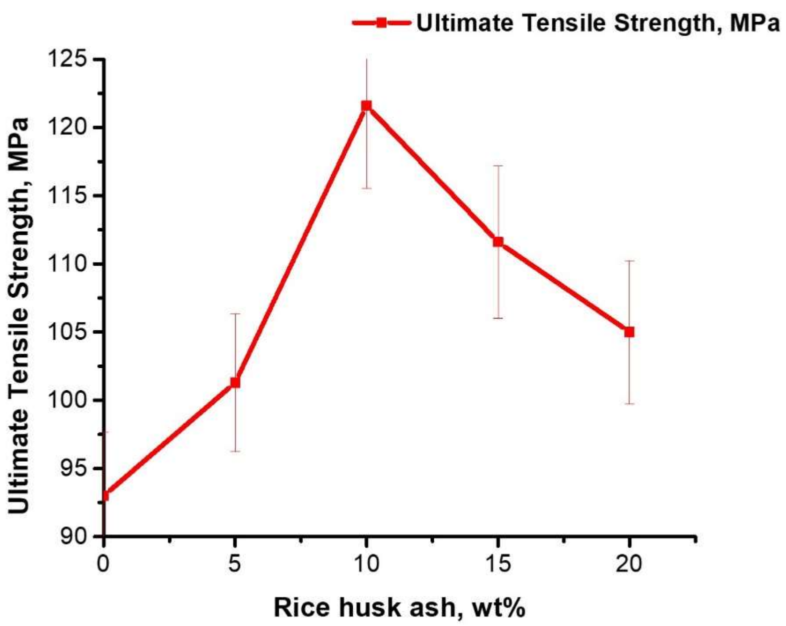

Figure 6. Tensile values at different wt% of rice husk ash.

The tensile results as presented in Figure 6 indicate that the rice husk ash reinforcement remarkably improved the tensile strength of the composites. The tensile strength increases to 101.3 MPa at 5% reinforcement addition to the matrix and increases further to the maximum of 121.6 MPa at 10% addition representing an increase of 30.8% over the unreinforced aluminium. The tensile strength value began to decline at the 15% addition of the rice husk ash and declined further to 105 MPa at 20% reinforcement addition. These findings agreed with those of Aigbodion et al., Hamouda et al. and Neelima et al. [29–32] and in similar studies. The tensile strength improvement of the composite is connected to the high Silicon content of the rice husk ash as presented in Table 2 which impacts strength and improves the grain boundary dislocation of the composites during the tensile testing. Other hard compounds present in the rice husk ash such as TiO_2, CaO, Fe_2O_3, Al_2O_3, and MgO which are also known to improve the strength of alloys contributed immensely to the observed high tensile strength of the composites at 5% and 10% rice husk ash addition [33,34]. However, at 15% and 20% addition, oxide segregation is possible due to the higher volume of reinforcement addition which lowers the strengthening precipitates and opens up sites for crack propagation thereby decreasing the load-carrying capability of the composites giving rise to a decrease in the tensile strength values at those points [30,35].

3.2. Impact toughness

The impact toughness result shown in Figure 7 revealed that moderate additions of the rice husk ash reinforcement to the aluminium matrix promote the impact toughness of the composite. The impact force increases from 75 J for the unreinforced aluminium to 77 J at 5 wt% reinforcement. At 10 wt% addition, the impact toughness increases to 81.5 J which is the highest value and represents an 8.2% increase over the control sample. Similar outcomes were disclosed by Usman et al. [35] and Aigbodion [36]. At this level, the dispersion of the rice husk ash into the aluminium matrix promotes interfacial adhesion and boosts the absorption energy of the composite with sufficient toughness and strength to endure the impact load [28,34]. The reduction in impact energy could emanate from the increase in the volume of SiO_2 particles in the matrix which if no longer segregated by the ductile aluminium matrix could cause crack propagation easily. Furthermore, the thermal differences between the reinforcement and the matrix generate elastic stresses which put the matrix into tension and the rice husk ash particles into compression, consequently promoting brittleness which probably reduces the impact energy [30,35]. The high quantity of reinforcement addition at 20 wt% could also cause insufficiency in the matrix material to establish the required bonding between the rice husk particles and aluminium matrix leading to wetting and a reduction in the impact energy.

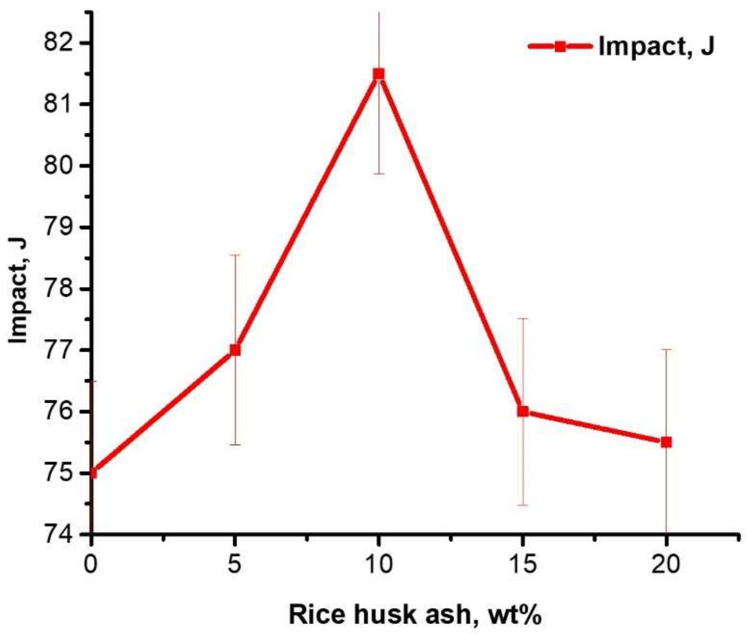

Figure 7. Impact toughness at different wt% of rice husk ash.

3.3. Hardness

The hardness values generally increase as the wt% additions of the rice husk ash increase (Figure 8). At 5% reinforcement addition, the hardness increases by 11.7% over the unreinforced aluminium alloy and increases marginally by 18% at 10 % addition. A sharp increase was noticed at the 15% particle addition to the matrix and increased slightly further at the 20% addition. The maximum Brinell hardness number (BHN) of 74.5 was obtained at the 20% reinforcement addition which represents an increase of 58.5 % over the unreinforced aluminium alloy. This result supports those of Saravan and Kumar, Aigbodion, and Shanmughasundaram et al. [19,36,37]. The homogenous spread of the reinforcement particles to the Aluminum matrix is a factor that favours the hardness increase. The hard-metallic compositions of the ash spread evenly along the grain boundary and promote intermetal-particulate bonding, enhancing the resistance to localized plastic deformation in the composite [38]. The presence of SiO_2, CaO, TiO_2, Al_2O_3, MgO, and Fe_2O_3 in the rice husk ash, which are known hard compounds, also contributed to the improvement in the hardness of the composites [33,34].

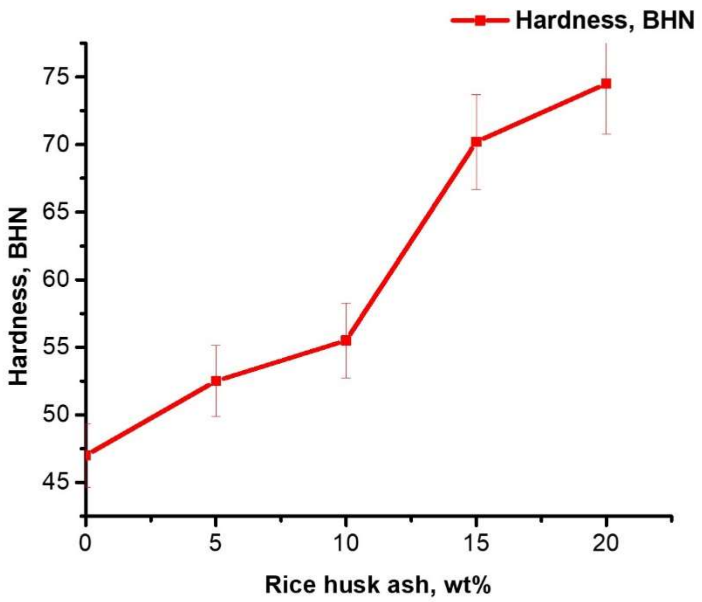

Figure 8. Hardness values at different wt% of rice husk ask.

3.4. Density

The density results as presented in Figure 9 show that the composites generally exhibited lower density than the aluminium matrix. The density reduces as the rice husk ash addition to the matrix increases. The lowest density of 2.46 g/cm^3 was recorded at the highest wt% addition of the rice husk ash particles. Similar trends in the density behaviour of aluminium matrix composites were equally reported by some researchers [28,35,39,40]. The reduction in density of the composites results from the lower density of the rice husk ash particles when compared to that of the aluminium. The addition of the rice husk particles in wt% fraction reduces the overall weight of the composites and the mass-to-volume ratio and consequently lowers its density. The reduction in the density of the composites indicates that lightweight aluminium composites are achievable by adding moderate rice husk ash particles as reinforcement.

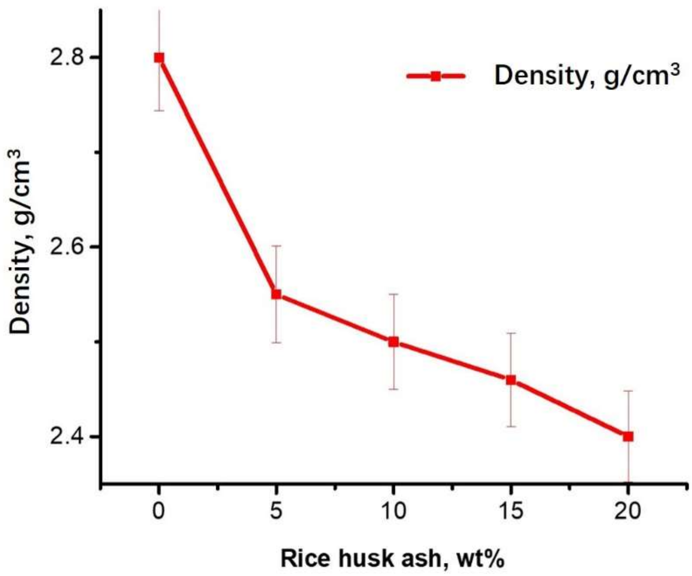

Figure 9. Density at different wt% of rice husk ash.

3.5. Microstructures

The optical microstructures of the composites are presented in Figure 10. The microstructures of the composites generally exhibited homogenous distributions of the rice husk ash into the aluminium matrix. This confirmed the reliability of the stir-casting technique used to produce the composites. The ash particles considerably spread along the grain boundaries of the aluminium matrix in the 5 and 10 wt% rice husk ash addition (Figure 10a,b). This homogenous dispersion of the reinforcement at these lower percentages of reinforcement additions could be attributed to the ease of stirring of the mixture, better wettability and matrix sufficiency to absorb the particles to form bonding and strengthening precipitates. This also explains the improved mechanical properties achieved at the lower percentage additions of the rice husk ash. However, little agglomeration of particles as highlighted in Figure 10d could be noticed at the highest weight fraction addition of the rice husk ash. The agglomeration could be linked to oxide segregation and poor wettability between the aluminium matrix and the rice husk ash. The rice husk ash modified the microstructures of the aluminium alloy, promoting interfacial bonding between the aluminium matrix and the ash particles causing the composites to develop more resistance to localized plastic deformation [28,41]. This accounts for the improvement in the tensile, hardness, and impact behaviour of the composites at medium wt% additions of the rice husk ash. At higher reinforcement additions, the occurrence of slight agglomeration of rice husk ash particles at some isolated points in the composites (Figure 10d) could weaken the adhesion between the aluminium matrix and the reinforcement and probably lead to the reduction in the impact and tensile strength observed in the 15% and 20% particulate additions.

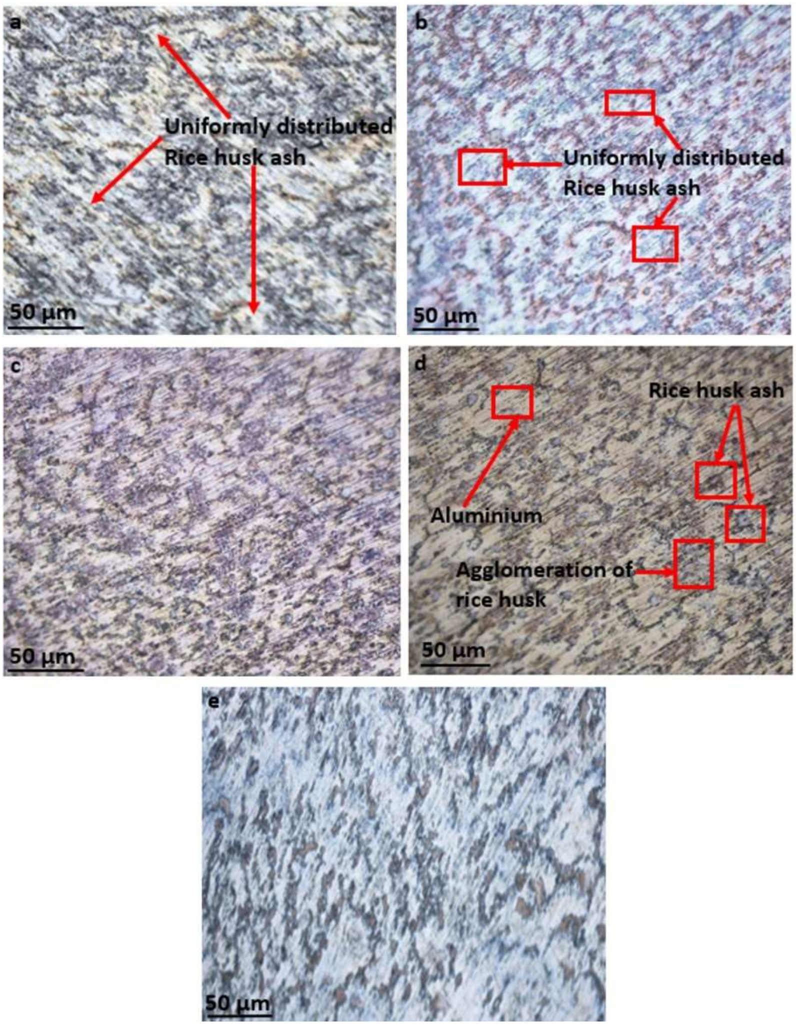

Figure 10. Microstructures of the composites: (a) 5 wt%; (b) 10 wt%; (c) 15 wt%; (d) 20 wt%; and (e) 0 wt%

The SEM and EDS results are presented in Figure 11 representing weight additions of 0%, 5% and 15% rice husk ash addition. The SEM shows distinct features as a result of the different weight additions of rice husk ash to the aluminium matrix. The EDS at 10 wt% reinforcement addition shown in Figure 11b reveals the presence of elements such as Mg, Si and O among others which are vital components of the rice husk ash responsible for the improvement in the mechanical properties. This agreed with similar reports by Alaneme et al. [42] and Aigbodion [36]. The EDS at 20% rice husk ash addition (Figure 11c) shows changes in the elemental composition of the composites with higher silicon content. This could be attributed to the high fractional addition of the rice husk ash which majorly contains SiO_2 as given in Table 2. Silicon addition to metals has been observed to improve the metal's mechanical properties. This also explains the better hardness performance of the composites when compared to the other composites and the unreinforced recycled aluminium. However, the noticeable agglomeration and segregation of the rice husk ash particles at the 20 wt% addition could lead to inhomogeneity in the orientation of the reinforcement and stress concentration thereby initiating cracks and pores (Figure 11c) which led to the observed poor impact and tensile performance of the composite at the 20 wt% reinforcement [31,36].

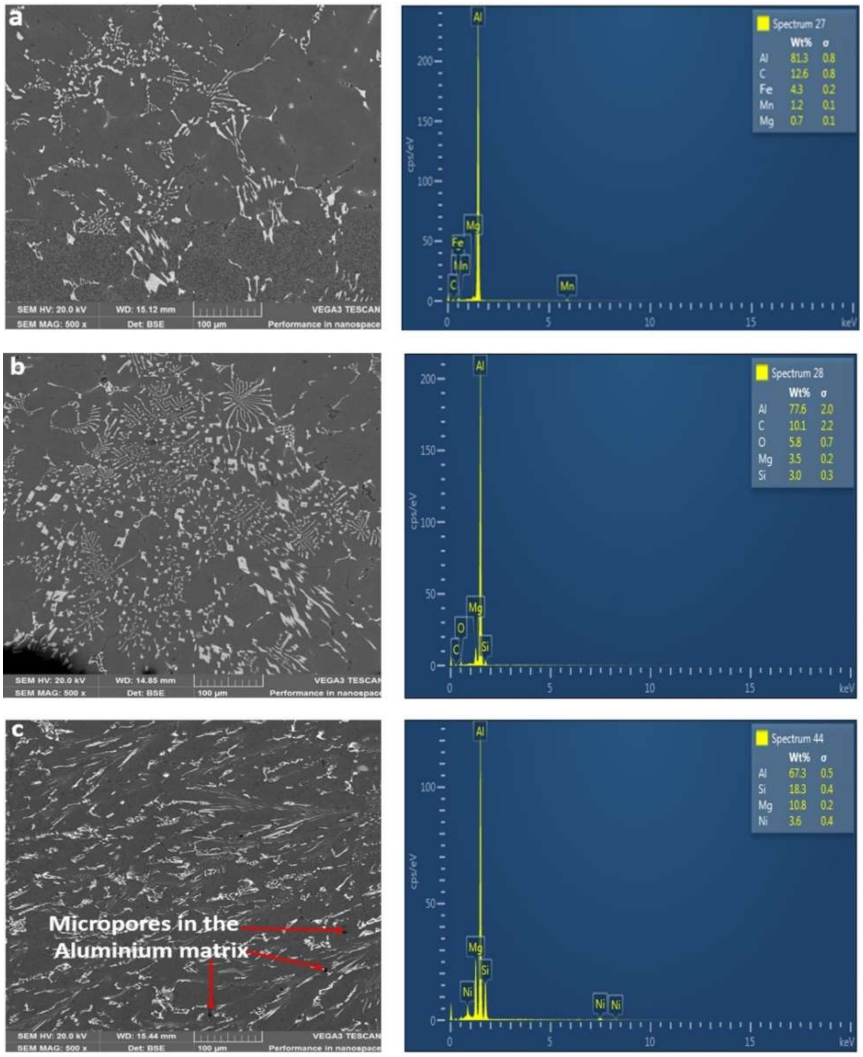

Figure 11. SEM and EDS analysis of the composites: (a) 0 wt%; (b) 10 wt%; and (c) 20 wt%.

4. Conclusions

1. Aluminium waste cans could be successfully reinforced with rice husk ash through the stir casting technique.

2. The resulting composites from the moderate addition of rice husk ash to the aluminium waste cans alloy matrix possess better tensile behaviour. The tensile strength increases as the fractional weight addition of the rice husk ash rises to 10 wt% and drops at 15 wt% and 20 wt% additions. The maximum tensile strength of 121.6 MPa was obtained at 10 wt% addition representing an increase of 30.8% over the unreinforced aluminium alloys. The impact toughness on the other hand improved at 5 wt% and 10 wt% rice husk ash addition but dropped at 15 wt% and slightly further at 20 wt%. The highest impact energy was obtained at 10 wt% reinforcement with a value of 81.5 J representing an 8.6% increase over the unreinforced aluminium. The hardness values increase as the wt% additions of the rice husk ash increase, giving a maximum hardness value of 74.5 BHN at the 20 wt% reinforcement addition which represents an increase of 58.5% over the unreinforced aluminium alloy. The composites' density reduces as the reinforcement's fractional weight additions increase with the

lowest density of 24.6 g/cm^3 recorded at the 20 wt% addition. The reduction in the density of the composites and the improved mechanical properties achieved up to the 10 wt% of reinforcement addition implies that lightweight aluminium composites with good mechanical properties are achievable with a moderate introduction of rice husk ash to the matrix.

3. The microstructures revealed a uniform dispersion of the rice husk ash particles into the aluminium matrix although little agglomerations could be noticed at higher percentages of the reinforcement additions to the matrix. The SEM and EDS analysis revealed the particle distributions in the composites in line with the composition of the rice husk ash.

4. Generally, the addition of the rice husk ash to the recycled aluminium waste cans improved the mechanical properties of the produced composites while reducing their density. These two factors accomplished in this work are key considerations in material selection and design for lightweight engineering applications. For instance, in the aerospace and automobile industries, the quest for lightweight materials to reduce the weight of aircraft and automobiles thereby saving fuel and improving the overall efficiency of the engines has led to some design and material considerations such as low density and high strength materials for the construction of fuselage, aircraft structures and automobile components to reduce weight. This study is a significant contribution towards meeting the quest for lightweight materials in automobile, aerospace, and other industries as a result of the ease, cheaper production techniques, availability of materials, sustainability, positive environmental impact, low-density, and improved mechanical strength of the composites. These advantages made the composite a promising alternative to the carbon fibre-reinforced composites and polymer matrix composites currently in use in aerospace, automobiles, and other industries.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Authors contribution

Olatunji P Abolusoro: conceptualization, material sourcing, casting operations, characterization, analysis, original draft preparation, writing, review and editing; Moshibudi Caroline Khoathane: conceptualization, characterization, analysis, supervision, review and editing, resources; Washington Mhike: conceptualization, characterization, supervision, analysis, review and editing, resources.

Conflict of interest

The authors declare no conflict of interest.

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