Microstructural characteristics and mechanical behaviour of aluminium matrix composites reinforced with Si-based refractory compounds derived from rice husk

Adeolu Adesoji Adediran¹,²*, Kenneth Kanayo Alaneme²,³, Isiaka Oluwole Oladele² and Esther Titilayo Akinlabi⁴

Abstract: The microstructural characteristics and mechanical behaviour of aluminium matrix composites reinforced with Si-based refractory compounds (SRC) derived from rice husk were investigated. The reinforcement materials (SRC) were synthesized using a carbothermal processing technique. The reinforcement was used to prepare a 10 wt.% Al-Mg-Si alloy-based composite using a double stir casting process. The composites produced were characterized using microhardness, tensile properties, scanning electron microscopy (SEM), and X-ray diffractometer (XRD). From the results, A1650, C1650, and A1600 grades of the samples show more resistance to indentation due to the high proportion of hard SRC in the reinforced materials. Superior elongation values were observed for these composites A1650, C1650 and A1600 grades, respectively. The grades A1250, B1250, and C1250 series had the least toughness values within the range of 20–37% as compared to the...
control sample. For all composites under examination, the percent porosity was noted to be less than 4% and the strain to fracture was within 24–38%. Higher intensity of SiC was observed from the XRD spectrum and the formation of intermetallic materials. The tensile fracture surface morphologies of the composites produced were similar, showing a ductile dimple-like structure. The formation of a micro-crack and micro-void was also observed along the interphase.

**Subjects:** Medicine; Composites; Materials Processing; Metals & Alloys

**Keywords:** reinforcement; metal matrix; SiC; composite; Al-Mg-Si alloy; morphology

### 1. Introduction

The choice of aluminium matrix composites (AMCs) in aerospace, structural, and automobile industries has been attributed to their unique properties, such as good wear resistance, low fabrication cost, low density, and high strength weight ratio (Shaikh et al., 2019; Singh & Chauhan, 2016; Suthar & Patel, 2018; Adediran et al., 2020). Besides, the characteristic attributes such as good corrosion resistance, lightweight, high thermal conductivity, and low processing cost make aluminium a choice material for metal matrix (Natarajan et al., 2006). Researchers over the years have deployed agro-waste as reinforcement material in the design of AMCs. Some utilized them as partial replacement along with synthetic ceramic reinforcement materials (Bodunrin et al., 2015; Alaneme et al., 2018) and also, with other synthetic materials (Alaneme et al., 2018; Verma & Vettivel, 2018) or in the development of hybrid composites (Shaikh et al., 2019; Alaneme et al., 2013a). Synthetic reinforcements such as silicon carbide (SiC) were previously synthesized using the Acheson process (Acheson, 1893). Silica sand and carbon were used simultaneously as source materials in an electric furnace-based reactor. However, the challenge in accessing these starting materials in the developing countries is of concern, coupled with the high processing techniques involved. Other processing routes such as carbothermal reduction of silica (Adediran et al., 2018); chemical vapour deposition (Zhang et al., 2016); powder mixing (Pezzotti & Sakai, 1994); sol-gel processes (Ebrahimpour et al., 2014); laser pyrolysis (Coupe et al., 2012) have been reported by the authors. The state-of-the-art facilities and the energy burden associated with the aforementioned processing routes pose a challenge to the developing countries. Carbothermal synthesis route is a cost-effective process for producing Si-based refractory compounds. Agro-waste materials containing high silica materials are easily and readily found within Nigeria. The environmental impact their disposal causes can be harnessed by converting them to Si-based refractory compounds (Adediran et al., 2019, 2018). Furthermore, the motivation behind the use of agro-waste as reinforcement is informed by the low-density property, low cost, and accessibility of these materials. Studies have shown that agro-wastes can either be used as precursor materials (Adediran et al., 2018) or processed into ash before further synthesis (Prasad et al., 2011; Alaneme et al., 2013a; Edoziuno et al., 2021; Madakson et al., 2012). These processed ashes were added as complementary reinforcement using different processing routes in the development of AMCs. Some of these are processes are liquid infiltration, rheocasting, double stir casting, compocasting, among others (Alaneme et al., 2018; Kala et al., 2014; Shabani & Mazzahery, 2013). However, double stir casting has been widely used over the years by researchers owing to its flexibility, simplicity, and viability (Prasad & Krishna, 2011; Alaneme et al., 2018; Ramanathan et al., 2019; Singh & Chauhan, 2017).

The challenge of accessing synthetic reinforcement materials in developing countries has been a concern for researchers (Prasad, 2016; Alaneme & Ajayi, 2017). To this end, agro-waste materials are highly sort after as potential materials for the synthesis of Si-based refractory compounds. In the previous work, Adediran et al. (2018) have successfully synthesized Si-based refractory compounds (SRC) from rice husk (RHS) via a carbothermal processing route. This SRC comprises a good percentage of silicon carbide and other refractory compounds in their structures. Thus, making them a potential reinforcement material in the design of AMCs (Akbar et al., 2020). Also, RHS
possesses a good percentage of silica, hematite and alumina as major refractory oxides in its structure (Dinaharan et al., 2017). However, the elastic modulus of silicon carbide (SiC) ranges between 50 and 70 GPa, which is relatively in line with that of aluminium (60 GPa) (Chakrapani & Suryakumari, 2020). Similarly, the elastic modulus of alumina ranges between 320 and 380 GPa, while that of silicon carbide is between 400 and 450 GPa (Alaneme et al., 2013a). There appears to be a sparse literature on the characterization of AMCs reinforced with Si-based refractory compounds derived from RHs. The current study attempts to explore the mechanical and microstructural characteristics of aluminium metal matrix composites developed from Si-based refractory compounds of RHs. The data from these findings would add to the existing database of cost-effective and technically efficient secondary reinforcement phase to improve aluminium metal matrix composites.

2. Materials and methods

2.1. Materials

Al-Mg-Si alloy (AA 6063) was used as a matrix in the composite production, and the elemental composition is presented in Table 1. Rice husks used as precursor materials were sourced from Igbemo Ekiti, Ekiti State, Nigeria. A carbothermal processing technique was used for the production of the Si-based refractory compounds (SRC) at a temperature window of 900–1650°C at a heating rate of 10°C/min in a controlled environment as described by Adediran et al. (2018). The morphology of the reinforcements is presented in Figure 1a, b, c, d, e, f, and g, respectively. The average particle size of the reinforcements varied from 40 to 50 μm. Details about the constituents of the reinforcement phases are as presented in Tables 3 & 4 respectively. The products from these reaction systems were used as reinforcement in the composite production. Table 2 shows the chemical composition of the rice husk used.

| Table 1. Elemental composition of Al-Mg-Si alloy |
|-----------------|----------|
| Element         | Wt.%     |
| Magnesium (Mg)  | 0.35     |
| Silicon (Si)    | 0.59     |
| Manganese (Mn)  | 0.35     |
| Copper (Cu)     | 0.012    |
| Zinc (Zn)       | 0.002    |
| Titanium (Ti)   | 0.057    |
| Iron (Fe)       | 0.47     |
| Nickel (Ni)     | 0.035    |
| Aluminium (Al)  | Balance  |

| Table 2. Elemental composition of rice husk ash |
|-----------------|----------|
| Element         | Wt.%     |
| Silica, SiO₂    | 91.81    |
| Carbon, C       | 4.91     |
| Calcium oxide, CaO | 1.35   |
| Magnesium oxide, MgO | 0.50 |
| Potassium oxide, K₂O | 0.41 |
| Hematite, Fe₂O₃ | 0.29     |
| Others          | 0.73     |
Figure 1. Showing the scanning electron image of reinforcements used for the production of the composite (a) A1 (b) B1 (c) C1 (d) A (e) B (f) D and (g) conventional SiC used for the development of D1.
Table 3. Variation in yield of selected Si-based refractory compounds processed at higher temperature interphase used for composites reinforcement (Adediran et al., 2018)

| Designation | 3 C-SiC | C | 2 H-SiC | 6 H-SiC | 4 H-SiC | SiC |
|-------------|---------|---|---------|---------|---------|-----|
| A1          | 44.96   | 28.75 | 6.28    | -       | -       | 11.8|
| B1          | 9.11    | 1.8  | 1.02    | 48.46   | 7.84    | 7.97|
| C1          | 0.15    | 4.53 | -       | 3.13    | -       | -   |

Table 4. Variation in yield of selected silica-based polytypes processed at 1250°C temperature interphase used for composites reinforcement (Adediran et al., 2019)

| Designation | Cristobalite | Tridymite | Fe₂O₃ | Quartz | g   |
|-------------|--------------|-----------|-------|--------|-----|
| A           | 47.20        | 7.55      | 1.63  | 19.45  | 24.17|
| B           | 44.51        | 2.38      | 0.06  | 12.52  | 40.54|
| D           | 50.44        | 2.49      | 0     | 8.78   | 38.20|

Table 5. Sample designation, reinforcement in 10 wt.% and reinforcement history

| Sample designation | reinforcement history                                                                 |
|--------------------|----------------------------------------------------------------------------------------|
| A1650              | SRC was synthesized at 1650 °C without catalyst.                                         |
| C1650              | SRC was synthesized at 1650 °C in a catalytic environment.                               |
| A1600              | SRC was synthesized at 1600 °C without catalyst.                                         |
| A1250              | SRC was synthesized at 1250 °C without catalyst.                                         |
| B1250              | SRC was synthesized at 1250 °C with the initial powder unconditioned and later treated in a catalytic environment |
| C1250D1            | SRC was synthesized at 1250 °C with the initial powder conditioned in a catalytic environment. conventional SiC. |

2.2. Composites production

The production of the Al-Mg-Si alloy matrix composites reinforced with Si-based refractory compounds from rice husk was performed using a two-step stir casting process as reported by Alaneme and Sanusi (2015). The process began with the determination of the amount of Si-based refractory (SRC) required to produce 10 wt.% particle reinforced composites. The variations in the yield of selected Si-based refractory compounds processed at higher temperature interphase used for composite reinforcement are presented in Tables 3 and 4, respectively. The SRC were preheated before the casting process at a temperature of 200–280°C to eradicate dampness and improve the wettability of the molten matrix following Alaneme and Aluko (2012). The Al-Mg-Si alloys were then charged into the crucible furnace (gas-fired with a temperature probe) and heated to a temperature of 710°C ± 30°C to ensure a complete melt. The melt was allowed to cool to a semi-solid state at a temperature of about 610°C and stirred manually for 10 min. The semi-solid mixture was again heated to 710°C ± 30°C and stirred with a mechanical stirrer operated at 350 rpm for another 5-10 min before casting into sand moulds with metallic chills around the mould. The composites designation and the processing history of the reinforcement are detailed in Table 5.

2.3. Composite density & percentage porosity

The evaluation of the composites theoretical density was done using the relation stated by Alaneme et al. (2013a) which implies that:
\[
\rho_{\text{Al-Mg-Si/SRC RH}} = \frac{w_{\text{Al-Mg-Si}} \times \rho_{\text{Al-Mg-Si}} + w_{\text{SRC RH}} \times \rho_{\text{SRC RH}}}{100}
\]  

where \(\rho_{\text{Al-Mg-Si/SRC RH}}\) is the composite density,

\(w_{\text{Al-Mg-Si}}\) is the weight fraction of Al-Mg-Si alloy,

\(\rho_{\text{Al-Mg-Si}}\) is the density of Al-Mg-Si alloy,

\(w_{\text{SRC RH}} \times \rho_{\text{SRC RH}}\) is the wt. fraction of Si-based refractory compounds from rice husk,

\(\rho_{\text{SRC RH}}\) is the density of the Si-based refractory compounds.

The experimental density of each composite produced was evaluated by dividing the measured weight of each sample by its measured volume using a digital weighing balance (GK 320-GS 2202) with a tolerance of \(\pm 0.001\).

The percentage porosity for each of the composites was computed using the values of the experimental density and the theoretical density following Alaneme et al., 2014.

\[
\%\text{porosity} = \frac{\rho_{\text{th}} - \rho_{\text{ex}}}{\rho_{\text{th}}} \times 100\%
\]

Where \(\rho_{\text{th}}\) is the theoretical density \((\text{g/cm}^3)\), and \(\rho_{\text{ex}}\) is the experimental density \((\text{g/cm}^3)\).

2.4. Mechanical properties

2.4.1. Hardness measurement

The microhardness test was evaluated on the composites developed using a standard procedure. The samples were machined and polished to obtain a smooth plane surface before the test was conducted following ASTM E92-17 standard (Astm, 2017). A microhardness tester FM-800 was used at 100 gf load at 15 s dwell time, and an average of 10 indentations were taken within the margin of \(\pm 2\%\).

2.4.2. Tensile testing

The tensile properties of the composites developed were determined at room temperature using an Instron universal testing machine. A strain rate of \(10^{-3}$/s\) was used with a specimen dimension of gauge length 30 mm and diameter of 5 mm following Alaneme and Odoni (2016). The test procedures were guided by the recommendation of ASTM E8/E8M-16a standard (ASTM E8/ E8M-16a, 2016). Triplicate tests were performed for each composite to ascertain the repeatability of the results.

2.4.3. Fracture toughness

Circumferential notch tensile (CNT) testing method was used for the fracture toughness determination as reported by Alaneme (2011). Samples for the test were machined to a gauge length of 30 mm, with a specimen diameter of 6 mm, a notch diameter of 4.2 mm, and 60° notched angle. The samples were later subjected to tensile loading to fracture using a universal tensile testing machine. The fracture toughness calculation was done from the fracture load \((p_f)\) obtained from the CNT specimens load-extension plots. The equation provided by Dieter (1988) was used in the final determination of the fracture toughness as corroborated by Alaneme and Ajayi (2017). Triplicate tests were done for each sample to ensure their reproducibility.
The fracture toughness of these composites was determined using the relations by Nath and Das (2006).

\[
KIC = \frac{P_F}{D^{\frac{1}{2}}} \left[ 1.71 \left( \frac{D}{d} \right) - 1.27 \right]
\]

where \( D \) and \( d \) are the specimen diameter and the diameter of the notch section, respectively.

Plane strain conditions and by extension, the validity of the fracture toughness values obtained was determined using the relations by Nath and Das (2006).

\[
D \geq \frac{(KIC)^2}{(\sigma_y)}
\]

### 2.5. XRD Characterization

X-Ray Diffraction (XRD) analysis was done on the composites to determine the phases present in the composites produced. The XRD was operated at 40 kV, and at 45 mA, samples were scanned at a speed of 2°/min in the range of 20 from 10° to 90°. The samples were prepared for XRD analysis using a backloading preparation method (Ramezani et al., 2021). They were analyzed with a PANalytical Empyrean diffractometer with PIXcel detector and fixed slits with Fe filtered Co-Kα radiation (\( \lambda = 1.54060 \)). The phases were identified using X'Pert High Score Plus software.

### 2.6. Microstructural characterization

Optical microscope (Olympus BX51M) was used for analyzing the microstructural features of the composites produced. Additionally, the surface morphology and fracture surface determination, and elemental composition were determined using JSM-7800 F extreme resolution analytical field emission scanning electron microscope equipped with an energy-dispersive spectroscopy (EDS). The scanning electron microscope was operated at 15 kV and a working distance of 15 mm (Ramezani et al., 2020; Hoseinzadeh et al., 2017). Selected areas of interest were focused and micrographs were taken for samples requiring SEM and EDS analysis (Ramezani et al., 2021; Hoseinzadeh et al., 2017). Before the microscopic examination, the samples were metallographically prepared using a series of grinding and polishing steps. Samples were then etched using Keller’s reagent (1.0 ml HF, 1.5 ml HCl, 2.5 ml HNO₃, 95 ml water).

### 3. Results and discussion

#### 3.1. Microstructure

Representative SEM micrographs and EDS analysis of the composites produced are shown in Figure 2(a, b, and c). The Si-based refractory compounds (reinforcement) were fairly dispersed in the matrix (Al-Mg-Si alloy). The EDS spectra also show the peaks of Si (silicon), Mg (magnesium), Al (aluminum), C (carbon), and O (oxygen). The presence of these elements confirm that SiC and Al-Mg-Si alloys are the main reinforcement and matrix, respectively. However, the presence of oxygen among others shows that it is partly from the silica phase of the rice husk. Similar observation has been reported by Alaneme and Sanusi (2015). From Figure 2(d, e, f, and g), representative optical microscope images for Al250, B1250, C1250, and D are shown. Figure 2(d) shows a higher dispersion of Si-based refractory in the matrix. The grain boundaries were, however, obvious in Figure 2(e), while (f) shows a relative dispersion of the reinforcement within the Al-matrix. However, there were few cracks noticed in the structure.

#### 3.2. Structural characterization

The XRD result is as presented in Figure 3. It shows the various diffraction patterns of the phases formed at varying 2theta values.

Figure 3 shows the variation in phases in the composites developed at different two theta values. The presence of SiC was evident in the phases identified in the XRD analysis and were characterized by high peak intensities. It is evident that the constituent elements in the matrix reacted with the Si-based refractory compounds, thus forming different phases in the composites.
developed. It is noted that there are other phases with lower intensity such as wustite (Fe$_{30}$O$_{36}$), spinel (MgAl$_{16}$O$_{32}$), and periclase (Mg$_{4}$O$_{4}$) also identified in the spectra. The role played by intermetallic compounds during the solidification of the composites developed has been reported by Yildirim and Ozyurek (2013) and Zulfia et al. (2007). Estatite with chemical formula Mg$_{14.56}$Fe$_{1.20}$Si$_{15.76}$Al$_{0.24}$O$_{48}$ and manganese silicide (Mn$_{10}$Si$_{6}$) have noticeable peaks in the phases for the compound identified in the spectrum. The formation of these compounds implies that there was...
Figure 2 (Continued).

(d) 
Particles agglomeration

(e) 
Reinforcement phases
Matrix phases

(f) 
Reinforcement

Figure 3. XRD patterns of the composites developed.
Figure 4. Variation of hardness value of the composites.

Figure 5. (a) Variation of the ultimate tensile strength of the composites. (b) Variation of yield strength of the composites.
an interface/chemical reaction between the elemental constituents in the composite matrix and the SRC.

3.3. Mechanical behaviour

3.3.1. Microhardness
The variations in the microhardness values are as presented in Figure 4.

It is noted that from Figure 4, the A1650, C1650, and A1600 grades of composites developed had higher hardness values implying more resistance to indentation due to the high proportion of hard SRC in the reinforced materials (Table 4). The SRC withstands the major load transferred by the matrix in the composites developed. Similar behaviour was reported by Ravikumar et al. (2017). It is ultimately inferred that the increment in the hardness values observed in A1650 sample might be attributed to the high proportion of SiC polytypes in the refractory compounds used as reinforcement (Table 3) for the production of the composite (Adediran et al., 2018). However, the presence of silica polytypes partly appearing as cristobalite phase (softer material) resulted in the reduction in hardness value, as observed in series A1250, B1250, and C1250, thus impeding the hardness level. A similar report was observed by different authors on the influence of silica phase on the harness value of composite materials (Alaneme & Sanusi, 2015; Shaikh et al., 2019). It is noted that the variations in the harness value are due to the different elastic behaviour of the reinforcement (SRC) and the matrix.

3.3.2. Tensile values
The representative variations in the ultimate tensile strength and the yield strength are as presented in Figure 5.

The representative ultimate tensile strength and yield strength values are as presented in Figure 5a & b. It is noted that the yield strength to some extent follows the trend in the hardness (Figure 4). The ultimate tensile strength (UTS) of C1650 gave the optimum value (for the composites developed) which is about 13.25% reduction when compared to the sample designated D1. Moreover, A1650 and A1600 had a range of 24–37.5% reduction in UTS for D1. This might be due to the interfacial bonding between the Al-Mg-Si alloy matrix and the relatively hard Si-based refractory compounds since there were variations in the yield of SiC in the reinforcement. It is worth noting that A1250, B1250, and C1250 all gave the lowest ultimate tensile value. Specifically, A1250 showed the least value with an approximate value of 44.92% reduction in the ultimate tensile strength. A similar trend was reported by Ravikumar et al. (2017) and Alaneme and Sanusi (2015). From Figure 5a, it was observed that as the yield of the Si-based refractory compounds increases in the matrix (Table 3), there appeared to be a corresponding reduction in the ultimate tensile strength. This trend was corroborated by Ravikumar et al. (2018); Singh and Chauhan (2016). It is evident that the strengthening is a result of the greater load-carrying capacity of the reinforcement, thus leading to higher work-hardening capacity and increase in resistance to plastic deformation in the composites developed (Chawla & Shen, 2001). An indirect strengthening occurred due to the variation in the thermal coefficient between the matrix and the SRC (Si-based refractory compounds) during cooling (Gladston et al. (2015); Chawla and Shen (2001)). It is worth noting that there was a marginal variation in the ultimate tensile strength in A1250 and B1250 compositions.

3.3.3. Strain to fracture, fracture toughness and porosity values
The variation of strain to fracture and fracture toughness values of the composites are presented in Figures 6 and 7, respectively.

From the variation in strain to fracture results presented in Figure 6, it is observed that C1650 grade shows a superior strain to fracture among the composite batches. However, when compared with D1 (control), it had about 52.9% increase in strain value. It is evident that this composite
grade was able to sustain plastic deformation; thus, it possesses a good ductility. However, composites A1250, B1250, C1250, and A1650 all had a strain to fracture increment ranging from 25% to 40% as compared to D1. Similarly, composite A1600 had about 2.9% reduction in strain value as compared to D1. Figure 7 shows the fracture toughness values of the composites produced, C1650 grade had about 15.3% increase in fracture toughness value when compared to D1 (control). However, previous work reported by Alaneme and Adewale (2013c) using 10 wt.% SiC in developing AMC showed a range of 6–7 MPam$^{1/2}$ fracture toughness values. This value was however attained after cold deformation was carried out on the samples to remove the deformity inherent after casting. It is noted that A1600, A1250, and C1250 recorded the least toughness values ranging from 20% to 37% when compared with sample C1650. However, they had a range of 13–26% reduction when compared with sample D1. The high proportion of Si-based refractory compounds in the matrix of the Al-Mg-Si alloy used as the matrix contribute to the reduction in the fracture toughness value observed in the composites developed. Additionally, SiC constitutes part of the reaction products in the Si-based refractory compounds. It is a hard ceramic reinforcement material that is liable to rapid crack propagation.
The variation in the density values for the composites developed is presented in Table 6. It is observed that the theoretical density had higher values as against the experimental, an indication that there were porosities in the composites developed. It was noted that for all composites, the percentage porosity was less than 4% which has been reported to be the maximum permissible in cast metal matrix composites (Alaneme & Sanusi, 2015).

Since the fractography image of the fractured surface of the composites developed shows an identical shape, a representative image showing the surface morphology of the fractured surface is presented in Fig. 8a, b, and c. It is however noted from Fig. 8a, b, and c that the fractured surface showed a ductile form of dimple structure likely due to shearing. The structure also showed some debris, pits and plastic deformation regions (Fig 8a & b), while a large burr due to plastic deformation and a continuous groove is shown in Fig. 8 c at higher magnification. It is apparent

| Sample Designation | Theoretical density (g/cm³) | Experimental density (g/cm³) | % Porosity |
|--------------------|----------------------------|----------------------------|------------|
| A1650              | 2.649                      | 2.565                      | 3.171      |
| C1650              | 2.649                      | 2.595                      | 2.039      |
| A1600              | 2.649                      | 2.559                      | 3.398      |
| A1250              | 2.649                      | 2.55                        | 3.737      |
| B1250              | 2.649                      | 2.546                      | 3.775      |
| C1250              | 2.649                      | 2.546                      | 3.888      |
| D1                 | 2.743                      | 2.690                      | 1.9        |

Figure 8. Representative SEM fractograph of the composite. Where (a, b, and c) are at magnification of 8000, 9000, and 10000 respectively.
that within the reinforcement-matrix interphase, there is a micro-crack and micro-void formation which might be due to debonding along this interphase (Chawla & Shen, 2001). Furthermore, it is evident that the cracks noticed on the fractured surface might have been as a result of the stress induced during tensile loading on the samples. This in turn creates a potential site for propagation before the final failure occurs. The fracture micro-mechanism of the reinforced AMCs is attributed to interfacial cracking, particle cracking and debonding. Equally of note is that this observation might have contributed to the reduction in the strength values observed in the composites produced. A similar trend was corroborated by Yildirim and Ozyurek (2013); Thirunghanam et al. (2007).

4. Conclusions
The microstructural characteristics and mechanical behaviour of aluminium matrix composites-reinforced with Si-based refractory compounds derived from rice husk was investigated in the current work. The results show that samples such as A1650, C1650, and A1600 showed more resistance to indentation due to the high proportion of hard Si-based refractory compounds in the reinforced materials. The Si-based refractory compounds withstand the major load transferred by the matrix in the composites developed and the strain to fracture for all composites were within the range of 15–46%. The tensile fracture surface morphology of all composites produced showed a ductile dimple structure. Intermetallic compounds were identified from the XRD pattern which play a significant role in the strength of the composites developed.

Acknowledgement
The authors appreciate the funding support for the APC from Pan African University for Life and Earth Sciences Institute, Ibadan, Nigeria.

Funding
The authors received no direct funding for this research.

Author details
Adeolu Adesoji Adediran1,2
E-mail: adadesoji@gmail.com
ORCID ID: http://orcid.org/0000-0001-9457-1071
Kenneth Kanayo Alaneme1,3
Isiaka Oluwole Oladele2
Esther Titilayo Akinlabi4
1 Department of Mechanical Engineering, Landmark University, Omu-Aran PMB 1001, Kwara State, Nigeria.
2 Department of Metallurgical and Materials Engineering, Federal University of Technology Akure, PMB 704, Ondo State, Nigeria.
3 Centre for Nanoengineering and Tribocorrosion, School of Mining, Metallurgy, and Chemical Engineering, University of Johannesburg, Johannesburg South Africa.
4 Pan African University for Life and Earth Sciences Institute, Ibadan, Nigeria.

Citation information
Cite this article as: Microstructural characteristics and mechanical behaviour of aluminium matrix composites reinforced with Si-based refractory compounds derived from rice husk, Adediran Adesoji, Adediran, Kenneth Kanayo Alaneme, Isiaka Oluwole Oladele & Esther Titilaya Akinlabi, Cogent Engineering (2021), 8: 1897928.

References
Acheson, E. G. (1893). Corborundum: Its history, manufacture and uses. Journal of the Franklin Institute, 136(3), 196–214. https://doi.org/10.1016/0021-9950(93)90311-H

Adediran, A. A., Alaneme, K. K., Oladele, I. O., & Akinlabi, E. T. (2019). Structural Characterization of Silica based Carbothermal Derivatives of Rice Husk. Procedia Manufacturing, 35, 436–441. https://doi.org/10.1016/j.promfg.2019.05.063

Adediran, A. A., Alaneme, K. K., Oladele, I. O., & Akinlabi, E. T. (2020). Effects of milling time on the structural and morphological features of Si-based refractory compounds derived from selected Agro-Wastes. Materials Today: Proceedings, 38(2), 928–933. https://doi.org/10.1016/j.matpr.2020.05.416

Adediran, A. A., Alaneme, K. K., Oladele, I. O., & Akinlabi, E. T. (2018). Processing and structural characterization of Si-based carbothermal derivatives of rice husk. Cogent Engineering, 5(1), 1–12. https://doi.org/10.1080/23311916.2018.1494649

Akbar, H. I., Surojo, E., & Ariawan, D. (2020). Investigation of Industrial and Agro Wastes for Aluminum Matrix Composite Reinforcement. Procedia Structural Integrity, 27, 30–37. https://doi.org/10.1016/j.prostr.2020.07.005

Alaneme, K. K. (2011). Fracture Toughness (KIC) evaluation for dual phase medium carbon low alloy steels using circumferential notched tensile (CNT) specimens. Materials Research, 14(2), 155–160. https://doi.org/10.1590/0100-179X-2011-05000028

Alaneme, K. K., Adewole, T., & Olubambi, P. (2014). Corrosion and wear behaviour of Al-Mg–Si alloy matrix hybrid composites reinforced with rice husk ash and silicon carbide. Journal of Materials Research and Technology, 3(1), 9–16. https://doi.org/10.1016/j.jmrt.2013.10.008

Alaneme, K. K., & Adebola, T. M. (2013). Influence of rice husk ash–silicon carbide weight ratios on the mechanical behaviour of Al-Mg–Si alloy matrix hybrid composites. Tribol. Ind., 35(2), 163–172. https://www.tribology.rs/journals/2013/2013-2/10.pdf

Alaneme, K. K., & Ajayi, O. J. (2017). Microstructure and mechanical behaviour of stir-cast Zn–27Al based composites reinforced with rice husk ash, silicon carbide, and graphite. Journal of King Saud University
Adediran Engineering (2021), 8: 1897928
https://doi.org/10.1080/23311916.2021.1897928

- Engineering Sciences, 29(2), 172–177. https://doi.org/10.1016/j.jskjes.2015.06.004
Alaneme, K. K., Akintunde, I. B., Olubambi, P. A., & Adewale, T. M. (2013). Fabrication characteristics and mechanical behaviour of rice husk ash – Alumina reinforced Al-Mg-Si alloy matrix hybrid composites. Journal of Materials Research and Technology, 2(1), 60–67. https://doi.org/10.1016/j.jmrt.2013.03.012
Alaneme, K. K., & Aluko, A. O. (2012). Fracture toughness (KIC) and tensile properties of as-cast and age-hardened aluminium (6063)-silicon carbide particulate composites. Scientia Iranica, Transactions A: Civil Engineering, 19(4), 992–996. https://doi.org/10.1016/j.sci.2012.06.001
Alaneme, K. K., Ekperusi, J. O., & Oke, S. R. (2018). Corrosion behaviour of thermal cycled aluminium hybrid composites reinforced with rice husk ash and silicion carbide. Journal of King Saud University - Engineering Sciences, 30(4), 391–397. https://doi.org/10.1016/j.jksues.2016.08.001
Alaneme, K. K., & Odoni, B. U. (2016). Mechanical properties, Wear and Corrosion Behavior of Copper Matrix Composites Reinforced with Steel Machining Chips. Engineering Science and Technolog for automotive applications, an International Journal, 19(3), 1593–1599. https://doi.org/10.1016/j.jestech.2016.04.006
Alaneme, K. K., & Sanusi, K. O. (2015). Mechanical and wear behaviour of rice husk ash-alumina-graphite hybrid reinforced aluminium based composite. Eng. Sci. Technol. Int. J., 18, 416–422. https://doi.org/10.1016/j.jestech.2015.02.003
ASTM E8/E8M-16a, standard test methods for tension testing of metallic materials. ASTM International, 2016, www.astm.org
Astm, E392–17, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials, ASTM International 2017, www.astm.org
Bodunrin, M. O., Alaneme, K. K., Chown, L. H. (2015). Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. Journal of Materials Research and Technology, 4(4), 434-445. https://doi.org/10.1016/j.jmrt.2015.05.003
Chakrapani, P., & Suryakumari, T. S. A. (2020). Mechanical properties of aluminium metal matrix composites-A review. Materials Today Proceedings. https://doi.org/10.1016/j.matpr.2020.09.247.(in press).
Chawla, N., & Shen, Y. (2001). Mechanical Behavior of Particle Reinforced Metal Matrix Composites . Advanced Engineering Materials, 3(6), 357–370. https://doi.org/10.1002/1527-2648(200106)3:6<357::AID-AEM357>3.0.CO;2-I
Coupe, A., Maskrot, H., Beut, E., Renault, A., Fontaine, P. J., & Chaffron, L. (2012). Dispersion behaviour of laser-synthesized silicon carbide nanowhiskers in ethanol for electrochemical infiltration. Journal of the European Ceramic Society, 32(14), 3837–3845. https://doi.org/10.1016/j.jeurceramsoc.2012.05.022
Dieter, G. E. (1986). Mechanical metallurgy. McGraw-Hill.
Dinaharan, I., Kalaiselvan, K., & Murugan, N. (2011). Influence of rice husk ash particles on microstructure and tensile behavior of AA6061 aluminium matrix composites produced using friction stir processing. Composites Communications, 3, 42–46. https://doi.org/10.1016/j.coco.2017.02.001
Ebrahimpour, O., Dubois, C., & Chaouki, J. (2014). Fabrication of sillilite-bonded porous SiC ceramics via a sol-gel assisted in situ reaction bonding. Journal of the European Ceramic Society, 34(2), 237–247. https://doi.org/10.1016/j.jeurceramsoc.2013.08.028
Edoziu, F. O., Adediran, A. A., Odoni, B. U., Uto, O. G., & Olayanju, A. (2021). Physico-chemical and morphological evaluation of palm kernel shell particulate reinforced aluminium matrix composites. Materials Today: Proceedings, 38(2), 652–657. https://doi.org/10.1016/j.matpr.2020.03.641
Gladston, J. A. K., Sheriff, N. M., Dinaharan, I., & Selvam, J. D. R. (2015). Production and characterization of rice husk ash particulate reinforced AA6061 aluminium alloy composites by compositing. 25, 683–691. https://doi.org/10.1016/j.mspro.2014.07.229
Hoseinzadeh, S., Ghasemiasl, R., Bahari, A., & Ramezani, A. H. (2017). n-type W03 semiconductor as a cathode electrochromic material for ECD devices. Journal of Materials Science: Materials in Electronics Volume, 28, 14446-14452.
Kala, H., Mer, K. K. S., & Kumar, S. (2016). A Review on Nanoparticles of A356/25SiCp aluminium matrix composites sliding against automobile friction materials. Wear, 261, 812–822
Nath, S. K., & Das, U. K. (2006). Effect of microstructure and notches on the fracture toughness of medium carbon steel. Journal of Naval Architecture and Marine Engineering, 3(1), 15–22. https://doi.org/10.3329/jname.v33i1.925
Pezzotti, G., & Sokai, M. (1996). Effect of a Silicon Carbide “Nano-Dispersion” on the Mechanical Properties of Silicon Nitride. Journal of the American Ceramic Society, 77(11), 3039–3041. https://doi.org/10.1111/j.1551-2916.1994.tb04545.x
Prosad, S. D., & Krishna, R. A. (2011). Production and mechanical properties of A356.2/RHA composites. Int. J. Adv. Sci. Technol, 33, 51–58. http://article. nadiapub.com/IJAST/vol33/5.pdf
Ramanathan, A., Krishnan, P. K., & Murdinhoja, R. (2019). A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities. Journal of Manufacturing Processes, 42, 213–245. https://doi.org/10.1016/j.jmp.2019.04.017
Ramezani, A. H., Hoseinzadeh, S., & Ebrahiminejad, Z. (2020). Statistical and fractal analysis of nitrogen ion implanted tantalum nanotubes. Applied Physics A, 126(6), 6. https://doi.org/10.1007/s00339-020-03671-7.
Ramezani, A. H., Hoseinzadeh, S., Ebrahiminejad, Z., Hantehzadeh, M. R., & Shafiee, M. (2021). The study of mechanical and statistical properties of nitrogen ion-implanted Tantault bulk. Optik, 225, 165628. https://doi.org/10.1016/j.ijleo.2020.165628
Ravikumar, K., Kiran, K., & Sreebalaji, V. S. (2017). Characterization of mechanical properties of aluminium tungsten carbide composites. Measurement, 102, 142–149. https://doi.org/10.1016/j.measurement.2017.01.045
Ravikumar, K., Prithvir, T., & Sreebalaji, V. S. (2018). Mechanical properties and characterization of zirconium oxide (ZrO2) and coconut shell ash (CSA) reinforced aluminium (Al 6082) matrix hybrid composite.
Adediran Publishing

Guaranteed High Immediate, Engineering your visibility online with Cogent and legacy publication and waivers citation dialog preservation OA to access for authors in developing regions. Cogent Engineering (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group. Publishing with Cogent OA ensures:

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

Submit your manuscript to a Cogent OA journal at www.CogentOA.com

© 2021 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

- Share — copy and redistribute the material in any medium or format.
- Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

- Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
- No additional restrictions

You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.