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Investigating the Effect of Coconut Shells on the Hardness, Density, and Wear Resistance of Aluminum

Ndudim Henry Ononiwu [1,2], Arize C. Igwe [1,2], Nnamdi C. Igwe [3], Chibuzo V. Ikwuagwu [1,2], Celestine N. Achebe [1]

[1] Department of Mechanical Engineering, University of Nigeria, Nsukka, Nigeria
[2] African Center of Excellence; Sustainable Energy and Power Development, University of Nigeria, Nsukka
[3] Department of Mechatronics Engineering, University of Nigeria, Nsukka
* Correspondence: ndudim.ononiwu@unn.edu.ng;

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Abstract: Aluminum matrix composites have grown to become a staple in materials engineering. This is due to its combination of properties, including improved mechanical properties, wear and corrosion resistance, and reduced weight. This research investigated the effect of coconut shells on the hardness, density, and wear resistance of aluminum. The selected fabrication route was stir casting. The composites were reinforced with coconut shells at 2 wt.% to 10 wt.% in increments of 2 wt.%. The microstructure of the investigated samples was characterized by a fairly uniform dispersion of the reinforcements, with minimal particle segregation and agglomeration. Compared to the unreinforced aluminum matrix, the hardness improved by up to 43.26%. The density decreased by up to 12.5% as reinforcement content increased, indicating significant weight saving. Wear resistance tests showed that the wear rate decreased with increasing weight fraction of the reinforcements, up to 55.29%, owing to the presence of hard, brittle particles that improve wear resistance by inhibiting grain boundary movement. The findings demonstrate the viability of coconut shell ash as a sustainable, low-cost reinforcement for producing lightweight, wear-resistant aluminum composites suitable for automotive and structural applications.

Keywords: aluminum matrix composites; reinforcements; coconut shells; hardness; wear resistance.

1. Introduction

Industrial applications, not limited to the automotive and aerospace industries, have been shown to prefer materials with a high strength-to-weight ratio and superior corrosion and wear resistance. This need has increasingly been met through the use of metals reinforced with sustainable materials. Sustainable materials for composite applications can enhance the properties of the matrix material while reducing environmental costs and overall costs [1,2]. Sustainable reinforcing materials used in the fabrication of aluminum matrix composites are either sourced from agricultural or industrial waste [3]. Several studies have shown that sustainable materials can be used to fabricate composites with properties including high strength, high corrosion and wear resistance, and reduced density [4–6]. In addition, researchers such as Moona *et al.* [2] have highlighted the need for environmental cost savings as a rationale for using these reinforcement categories in the fabrication of composite materials.

Such sustainable materials include fly ash, egg shells, coconut shells, red mud, bagasse, and palm kernel shells, among others. The research into these materials has shown that they can be put to good use, thereby reducing their indiscriminate disposal. Dwivedi and Mishra [5] highlighted the relative fabrication cost as a factor in adopting sustainable reinforcing materials over conventional reinforcing particles. Conventional reinforcing particles are synthetic materials that can be used to improve the properties of aluminum matrix composites through several mechanisms, such as load transfer and grain refinement [7, 8]. Such materials include SiC, Al_2O_3, B_4C, TiC, and carbon nanotubes. While these materials have been used successfully to improve the properties of the aluminum matrix, cost and environmental sustainability are factors that tend to limit their use [9]. This issue can be solved through the utilization of sustainable materials, which can be procured at little to no cost.

Donald *et al.* [10] fabricated a hybrid composite by reinforcing coconut shells with silicon carbide. The results showed an improvement in the hardness and tensile strength by 23.55% and 44.18%, respectively. Ononiwu *et al.* [11] successfully reinforced aluminum with eggshells and investigated selected properties. The results of the experiment showed a reduction in the density with increasing weight fraction of the eggshells. Further analysis revealed a 9.10% increase in tensile strength, with an increase in hardness also reported. Prakash *et al.* [12] investigated the effect of rock dust on the hardness of aluminum. The hardness increased with increasing weight fraction of the reinforcements from 39 BHN for the unreinforced aluminum to 78 BHN for the sample with 15 wt.% of the rock dust particles. Vinod *et al.* [13] reinforced Al-7Si-0.3Mg with fly ash and rice husk ash and reported an improvement in the microhardness from 61 HV for the unreinforced alloy to 82 HV for the sample reinforced with 7.5 wt.% rice husk and fly ash. The study also reported a 4.54% improvement in compressive strength. The wear studies revealed that the wear resistance of the fly ash and rice husk ash-reinforced samples improved compared to the unreinforced sample. Singh *et al.* [14] produced a hybrid aluminum matrix composite reinforced with Al_2O_3 and rice husk ash. The results showed that the composite's tensile strength improved by 42.5% and 72.5% compared to the Al 6063 matrix.

The literature reviewed shows that sustainable reinforcements can improve the properties of aluminum. This study therefore, aims to investigate the microstructure, hardness, density, and wear resistance of aluminum reinforced with coconut shell particles. By evaluating the effect of coconut shells on the highlighted properties, this research introduces a reproducible, low-cost, and environmentally friendly approach to fabricating lightweight materials suitable for use across various industries.

2. Materials and Methods

The aluminum ingot was sourced from Nsukka, Enugu State, Nigeria. A 4 kg aluminum ingot was procured for this study. The elemental composition of the aluminum ingot is summarised in Table 1.

Table 1. Elemental composition of the aluminum ingot used in the study.

Composition	Si	Fe	Mg	Cu	Al
%	0.5	0.18	0.6	0.01	98.71

Coconuts were sourced from the Ogige local Market in Nsukka, Nigeria. Coconut shells were extracted for use in the study. The coconut shells were washed in running water to remove any contaminants that might taint the fabrication process and, by extension, the results of the experiments. The washed coconut shells were subsequently dried in the open air for 3 days. Further drying was performed in an electric oven set to 80°C to remove any residual moisture. Milling of the coconut shells was done using a ball milling machine rotating at 180 rpm. The ball milling was carried out for 7 hours to ensure the samples were in the nano range. The milled coconut shells are depicted in Figure 1(a). The milled samples were afterward calcinated in the open air to reduce them to ash. The resulting ash was carbonized at a temperature of 800°C. Carbonization of the coconut shell particles was necessary to improve the wettability between the matrix and reinforcements, increase the carbonaceous content of the reinforcements, and improve the interfacial bonding of the reinforcements with the matrix [15,16]. The carbonized coconut shell particles are shown in Figure 1(b). The samples were passed through a sieve with a mesh size of 50 µm. All particles that passed through the sieve were retained and used for the study. The composition of the coconut shell particles is shown in Table 2. The samples used for this study are summarized in Table 3.

Table 2. Chemical composition of the coconut shell particles [17].

Composition	SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	Na_2O	MnO	ZnO	LOI
%	41.26	21.84	12.37	18.45	0.67	0.72	0.23	0.36	4.1

Figure 1. Images of **(a)** Milled coconut shells; **(b)** Carbonized coconut shell particles.

Table 3. Designation of the fabricated samples.

Samples	Aluminum matrix wt.%	Coconut shell reinforcements wt.%
A	100	0
B	98	2
C	96	4
D	94	6
E	92	8
F	90	10

For proper fabrication, the coconut shell reinforcements were weighed and preheated at 400°C. An electric furnace was heated to 750°C while a graphite crucible was preheated at 750°C. The graphite crucible was gradually preheated to the required casting temperature to avoid thermal shock. Prior to being charged into the crucible, the aluminum was cleaned, cut, and weighed according to the designations in Table 3. Melting of the aluminum was followed by degassing the molten metal with hexachloroethane tablets, which was necessary to eliminate hydrogen and oxidized slag from the melt. This stage was followed by the removal of slag formed during the melting and degassing of the aluminum melt. The preheated reinforcements were charged into the molten aluminum, followed by 1 wt.% magnesium powder of 100% purity. Magnesium further improves the wettability between the composite constituents. Mechanical stirring was performed for 10 minutes to ensure uniform dispersion of the reinforcements in the aluminum matrix. The resulting molten composite was poured into a predesigned sand mould shown in Figure 2(a), and the solidification and cooling process commenced. The fabricated samples are shown in Figure 2(b).

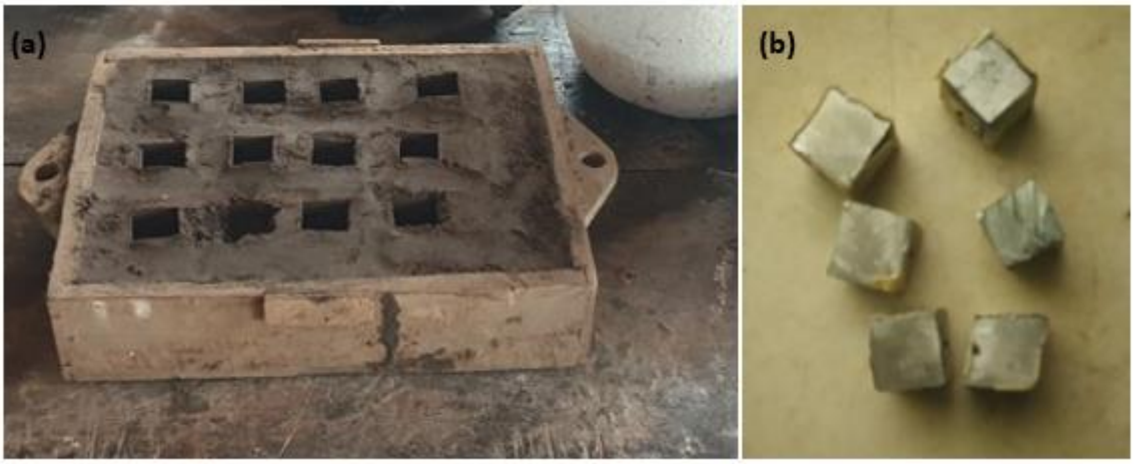

Figure 2. (a) Sand mould; **(b)** Cast samples.

The hardness of the cast samples was determined using the Vickers hardness tester. This test was conducted at room temperature (26°C). To assess the material's hardness and ensure replicability of results, five separate indentations were performed. Each indentation was performed under a constant load of 200 N, with a dwell time of 15 seconds to ensure consistent deformation. The measurements were taken at evenly spaced intervals across the sample surface to minimize variability due to localized microstructural differences. This approach ensured reliable data for subsequent analysis and comparison. The hardness value obtained after each indentation was recorded, and the average hardness of the 5 indentations was calculated. The resulting value was reported as the hardness for the sample. This was conducted for all the samples under consideration.

Using Archimedes' principle of volume displacement, shown in equation 1, the density of the cast samples was determined.

$$\rho_s = \frac{m}{v} \qquad (1)$$

Where ρ_s is the density of the sample in g/cm^3, m is the mass of the sample, v is the volume displacement.

The wear resistance was conducted using a pin-on-disc tribometer with a load of 20 N for 20 cycles under dry sliding conditions. Using the expressions in equations 2 and 3, the volumetric wear loss and specific wear rates were computed, respectively.

$$\Delta V = \frac{(w_1 - w_2)}{\rho} \qquad (2)$$

Where ΔV is the volumetric wear loss in cm^3, w_1 and w_2 is the initial and final weight, respectively, in g, while ρ is the density of the given sample.

The specific wear rate was calculated to give information on the rate of wear at the given load and sliding distance. This was obtained mathematically using the expression in equation 3.

$$W_s = \frac{\Delta V}{F \times S} \qquad (3)$$

Where W_s is the specific wear rate in g/Nm, F is the applied load in N, and S is the sliding distance in m.

3. Results and Discussion

3.1. Hardness.

The hardness of the investigated samples was characterized by a steady increase up to 8 wt.% coconut shell reinforcement, as evident in Figure 3. This accounted for a 43.26% increase in the hardness compared to the unreinforced aluminum. A decline from 30.80 HV for the 8 wt.% sample to 28.40 HV for the 10 wt.% sample was recorded from the experiment. The decline can be attributed to the increased viscosity of the molten, which is responsible for the segregation and agglomeration of the reinforcing particles. The improvement in the composites' hardness is due to strong interfacial bonding and proper wettability between the reinforcing particles and the aluminum matrix. Another reason for the improved hardness is the grain refinement brought about by the coconut shell reinforcements. The enhanced hardness of the cast composites can also be attributed to the formation of dislocations, which increased the dislocation density of the samples. The increased dislocation density is a direct consequence of the difference in the coefficient of thermal expansion of the matrix and the coconut shell particles. Furthermore, the presence of hard, brittle reinforcing particles increases hardness by limiting the relative mobility of individual grains when a localized load is applied [18].

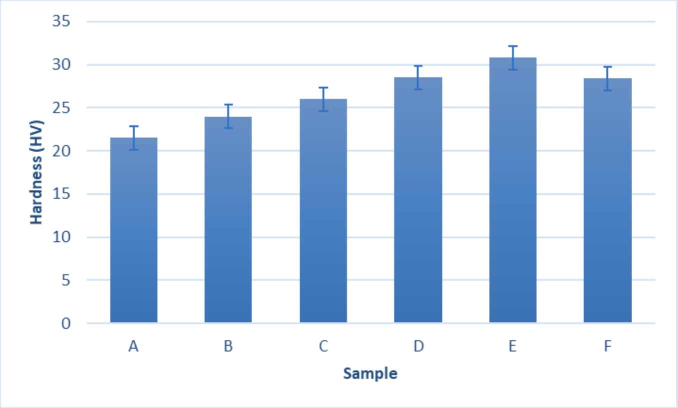

Figure 3. Vickers hardness values of cast samples.

3.2. Density.

In Figure 4, it is evident that the incorporation of coconut shell particles was responsible for the reduced density of the reinforced samples. The lower density of the coconut shell contributed to the reduced overall composite density.

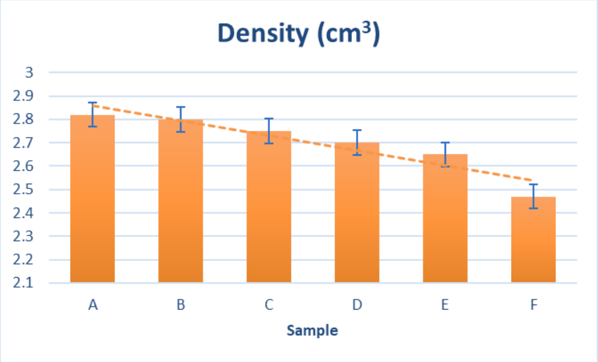

Figure 4. Density of the cast samples.

The investigation revealed that the density of the cast aluminum composite samples decreased with increasing weight fraction of the coconut reinforcing samples up to 10 wt.%.

Similar trends were reported in [19] and [20]. The density of the reinforcements decreased by 12.5% for the 10 wt.% coconut shell reinforced sample. The highlighted result indicates that coconut shell particles can produce lightweight aluminum matrix composites.

3.3. Microstructure.

Figure 5 shows the microstructure of the cast. The micrographs of the matrix show the presence of the α-phase, with the formation of a dendritic structure during post-casting solidification of the aluminum metal. From Figure 5, the microstructural analysis of the unreinforced aluminum showed the presence of minimal micro-pores that may have formed during the cooling of the cast. In sample C (Figure 5b), the micrograph showed fine, irregularly shaped particles. These particles were well-dispersed despite the formation of minimal clusters. These clusters may have resulted from incomplete mixing due to the density difference between the matrix and reinforcement phases. The coconut shell particles introduced significant matrix-particle interactions, which contributed to increased dislocation density and the impediment of grain boundary movement, thereby enhancing the hardness and wear resistance of the developed composites. The uniform dispersion of the reinforcement in the aluminum matrix indicates the wettability of the interfacial bonding. In sample F depicted in Figure 5c, the micrographs revealed a higher concentration of the reinforcement in the matrix. The increased concentration of particles in the aluminum matrix revealed more pronounced agglomeration and clustering of the coconut shell particles. In some instances, these agglomerates can act as stress concentrators, leading to localized porosity or matrix cracking under certain mechanical loading (as evidenced by the decrease in hardness for sample F) [21].

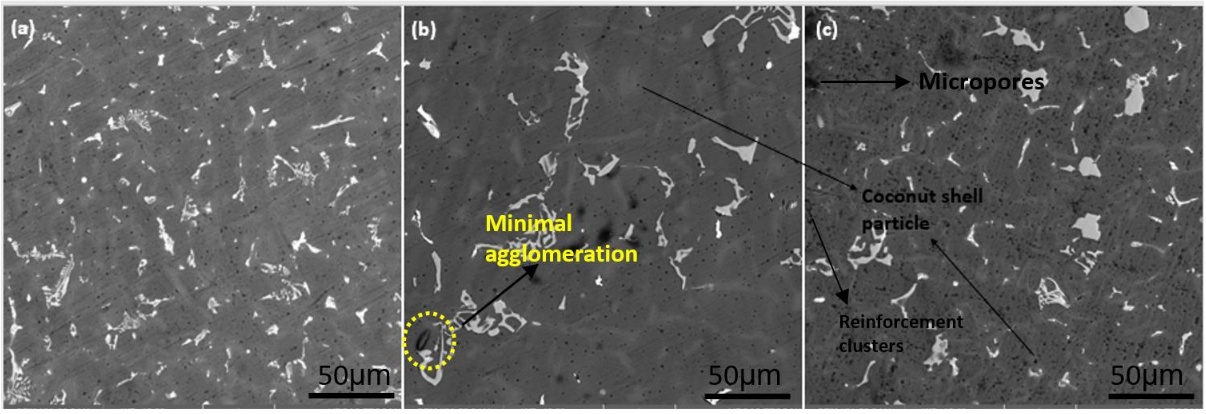

Figure 5. Micrographs of **(a)** Sample A; **(b)** Sample C; **(c)** Sample F.

3.4. Wear studies.

Figure 6 is a depiction of the wear rate of the cast samples. From the wear resistance study, the wear rate decreased with increasing coconut shell particle content. The wear rate decreased by 9.61%, 14.82%, 28.31%, 41.80% and 55.29% for the 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.% and 10 wt.%, respectively.

Due to the relatively softer surface of the unreinforced aluminum samples (as observed in the hardness test), the wear rate was highest in these samples. The reduction in wear resistance, in addition to the relatively soft surface, was also attributed to poor resistance to plastic deformation and abrasive wear that occur during sliding. The introduction of coconut shell reinforcements, shown in Figure 6, resulted in a consistent reduction in the wear rate across all reinforced samples.

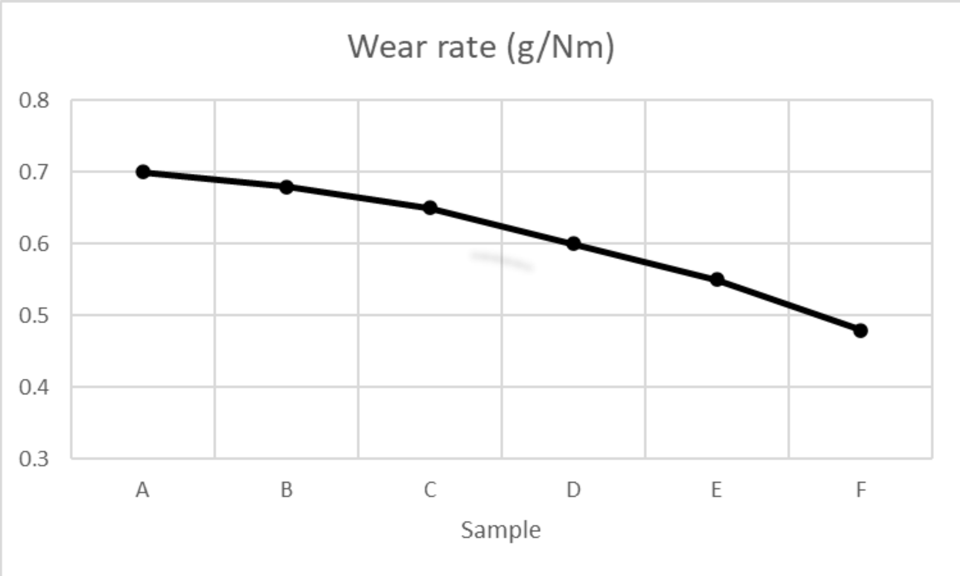

Figure 6. Results of the wear rate.

For sample B (2 wt%), the wear rate slightly decreased, suggesting that the presence of the coconut shell particles in the aluminum matrix resulted in the initial reduction of material removal during sliding. Samples B, C, and D also reported a consistent increase in wear resistance. This consistent improvement could be attributed to the improved interfacial bonding between the matrix and the reinforcement, brought about by better particle distribution. In sample F, it was observed that there was a notable decrease in the wear rate. In addition to the reason described for samples B to E, the increased weight fraction of the reinforcement formed a barrier that limited contact between the matrix and the abrasive surface.

Although Sample F showed a slight decrease (7.79%) in hardness when compared to Sample E, its wear resistance was the highest. This could be attributed to the predominance of surface mechanisms in wear performance. A denser distribution of hard coconut-shell particles in the matrix at higher reinforcement levels effectively reduces the real area of contact and protects the aluminum matrix from severe abrasion. Nevertheless, microstructural flaws and particle agglomeration resulting from increased reinforcement content may have been responsible for the decreased hardness.

Overall, multiple factors contributed to the improved wear resistance of the reinforced samples. These factors include the uniform dispersal of the reinforcing phase in the aluminum matrix, which reduces the impact of the applied load on wear propagation by acting as load-bearing members of the composite material. In addition, proper interfacial bonding between the reinforcing particles and the matrix could have also improved the composites' wear resistance by minimizing particle pullout during dry sliding between the 2 contacting surfaces. The coconut shell particles also improved the wear resistance of the composites by reducing the effective contact area during sliding wear, thereby limiting direct interaction between the abrasive and the composite surface [8].

4. Conclusion

The study was conducted to investigate the effect of coconut shells on the hardness, density, and wear resistance of aluminum. From the experiments conducted, it was found that the composites' hardness improved relative to the unreinforced aluminum matrix. The hardness was maximum at 30.80 HV, which translates to an increase of 43.26%. The density decreased with increasing weight fraction of the reinforcing particles, indicating that the coconut shell particles successfully reduced the sample weight. The wear resistance improved with increasing weight fraction of the reinforcing particles up to 10 wt.%. The wear rate was shown to decrease by 55.29% for the 10 wt.% sample. Based on the observed improvement in weight reduction, hardness, and wear resistance, the developed aluminum matrix composite is well-suited for a variety of applications. Such applications include automotive components, aerospace structures that have a demand for lightweight materials, agricultural machinery parts, and consumer appliances.

Author Contributions

Conceptualization, N.O. and A.I.; methodology, N.O.; formal analysis, C.I.; investigation, C.A.; resources, N.O.; data curation, N.I.; writing—original draft preparation, N.O.; writing—review and editing, A.I.; project administration, C.I.; funding acquisition, A.I. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Note applicable.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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