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Potentials of Snailshell as a Reinforcement for Discarded Aluminum Based Materials

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Abstract

Snailshells and discarded aluminium based alloys have low economic values and are mostly considered as environmental pollutants. However, recycling them for further application in material processing can create significant economic value. Snailshell particles are known for their hardness, and thus useful as good alloying element for aluminium based pistons. In this paper, the potential of snailshell particles as reinforcement agent in Al/snailshell particulate composites is reported. Snailshell particles of weight fraction ranging from 16 to 48 wt.% and size of 200, 400 and 600 μm were added to aluminium obtained from discarded aluminum pistons during casting. The microstructures of the composites were examined under optical metallurgical microscope. The tensile strength and hardness were measured based on the experiments conducted using Box Behnken design. The results showed that, at 48 wt.% and 600 μm particle size, the tensile strength and hardness are maximum (236 MPa and 48.3 HRF, respectively) compared to the tensile strength of 92.4 MPa and hardness of 29.2 HRF for the unalloyed samples. These increments are attributed to the uniform distribution of snailshells in the ductile aluminum matrix. It is concluded that both the tensile strength and hardness are significantly enhanced, and snailshells can be used as a low-cost reinforcement for engineering applications.

Keywords: *Snail shell, aluminum matrix composite, mechanical properties, reinforcement*

1. Introduction

Snailshells and discarded aluminium based components have low economic values, and are often considered as environmental pollutants. Consequently, effectively utilizing them can bring immense economic prosperity. Snailshell particles are known for their hardness, and thus considered as good alloying agent for aluminium based composites [1]. In practice, limited mechanical properties of aluminium and its alloys, mostly strength and hardness, adversely affect the rage of their applications [2, 3]. Improving mechanical properties of alloys to suit different applications constitutes a major concern during fabrication. Hence, interests are growing in the use of aluminium based metal matrix with improved mechanical properties and wear resistance, especially in the transport industries where light weight and enhanced friction and wear performances are the key objectives.

The growing requirement of materials with high specific mechanical properties and weight savings characteristic has increased significant research activities in recent times focusing primarily on further development of aluminium based composites [4-6]. Alloys with distinctive properties such as high stiffness, high strength, significant toughness and low density have promoted an increasing number of applications in different areas. The

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demand for cost-effective and high performance structural materials is pushing researchers to develop novel processing techniques [7].

A significant improvement in the properties of aluminum based composite (especially strength and stiffness) was obtained with the introduction of fibre reinforcement but the properties of the resulting composites are anisotropic. Particle-reinforced metal matrix composites (MMCs) are attractive in that they exhibit near-isotropic properties when compared to the continuously-reinforced matrices [8] and have better wear resistance [9-10]. In this study, aluminium matrix composite is produced from recycled aluminium pistons reinforced with snailshell particulates by stir cast process. The microstructure and the mechanical properties are obtained experimentally, studied and evaluated, and the results compared with those of as-cast aluminium pistons.

2. Experimental Procedure

2.1. Materials

The snailshells were obtained from a disposal site around local markets in Ogbomoso, Oyo State, Nigeria. Disposed aluminum pistons were collected from various automobile workshops in the same city. The snailshells were washed with water, oven dried - to remove water - and then broken into smaller pieces (Figure 1a). These were then milled at 250 rpm to particles of different sizes (Figure 1b). The particle size analysis was carried out following the recommended procedure in BS1377:1990. The particles were placed onto a set of sieves arranged in descending order of fineness (600, 400 and 200 μm) and shaken for 15 min as recommended by Hassan and Aigbodion (2013) and Shuhadah, Supri, and Kamaruddin (2008). The aluminum pistons were also washed and dried, and then broken into smaller pieces.

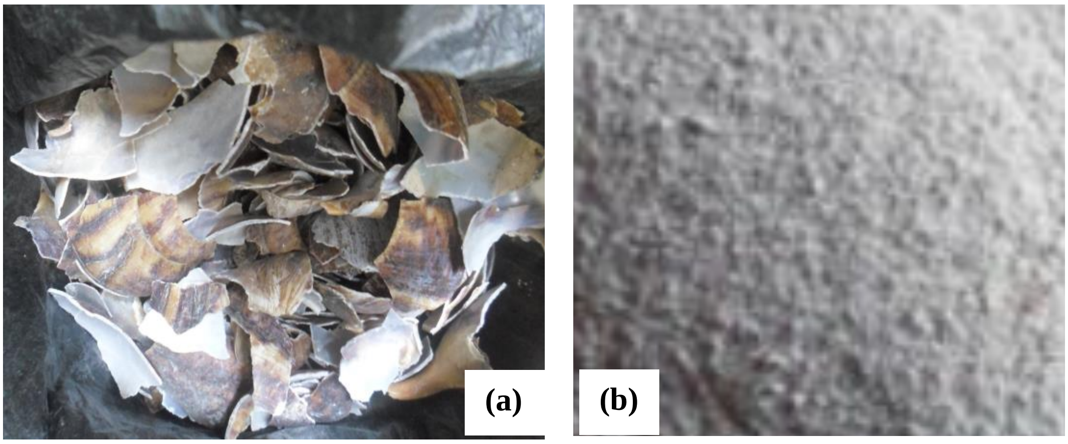


Figure 1. (a) Snailshells before Grinding (b) Uncarbonized Snailshell Particles

2.2. Experiment Design

Design of Experiment (DOE) technique was adopted because it enables designers to determine simultaneously the individual and interactive effects of many factors that could affect design outputs. With this, designers are able to produce robust and higher yield designs prior to production. Response surface methodology (RSM) was used because of the reduced number of experimental runs needed to provide sufficient information for statistically acceptable results [13]. Two input variables, weight fraction and particle size of the snailshells, were selected. The weight fraction was varied from 16 to 48 wt.% while the particles sizes were 200, 400 and 600 μm. Based on Box Behnken experimental design, the three levels of each of the two input variables required 17 sets of experiments (Table 1). The response variables were tensile strength and hardness of the composites.

Table 1. Parameters and Levels for Experimental Design

	Level		
Parameter	1	2	3
Reinforcement (wt.%)	16	32	48
Particle size (μm)	200	400	400

2.3. Casting Process and Sample Preparation

Aluminum pistons were melted in a 20 kg-capacity pit furnace at 660 ± 5 °C using double stir-casting method. A control sample (without filler addition) was cast by pouring the molten metal, into a preheated metal mould. Thereafter, the molten aluminum was poured into a red hot crucible containing 48% weight of 600 μm sized snailshell particles. The mixture was stirred manually for about 2 minutes to ensure uniform distribution of the particles in the aluminum matrix. The mixture was reheated, and then the melt was poured into a metal mould. It was thereafter left to solidify and cool to room temperature prior to stripping. This procedure was repeated for other samples.

After casting, small pieces of the composites were used for microstructural study using a metallurgical microscope (AXIObserverAIM). Parts of the composite were appropriately machined into tensile and hardness test samples. The hardness of the samples were determined using the Rockwell hardness tester on ‘‘F’’ scale (Frank Well test Rockwell Hardness Tester). The steel ball indenter is $^{1}/_{16}$ inch in diameter with a minor load of 60 kg and a major load of 100 kg. Its accuracy was confirmed by testing a standard block of hardness value of 101.2 HRF. The tensile test was conducted on an automatic electronic tensile testing machine. The test pieces were machined to the standard shape and dimensions as specified by the American Society for Testing and Materials (ASTM E18-79).

Samples for metallographic examination were polished and mechanically ground progressively on grades of SiC impregnated emery paper (80 - 600 size) using water as coolant. They were then polished using 1 μm size alumina polishing powder suspended in distilled water. Final polishing was done using 0.5 μm alumina polishing powder. Following the polishing step, etching was done using Keller's reagent. The microstructures were then observed using an optical microscope with built-in camera.

3. Results and Discussion

3.1. Microstructural Study

The microstructure of the unalloyed sample shows significant pores of varying sizes and shapes (Figure 3a) while that of the alloyed samples reveals irregular snailshell particles distributed in aluminum matrix (Figure 3b). This confirms that the snailshells consist of calcium carbonate ($CaCO_3$) in the form of calcite similar to the observation of Aigbodion and Hassan (2007). In addition, the particles are uniformly distributed. The distribution of snail shell particles is influenced by good wettability of the snailshell particles by the molten metal and good interfacial bonding between particles and matrix material. Good retention of the snailshell particles was clearly seen in the microstructures. These observations are similar to those of previous studies [12, 15, 16].

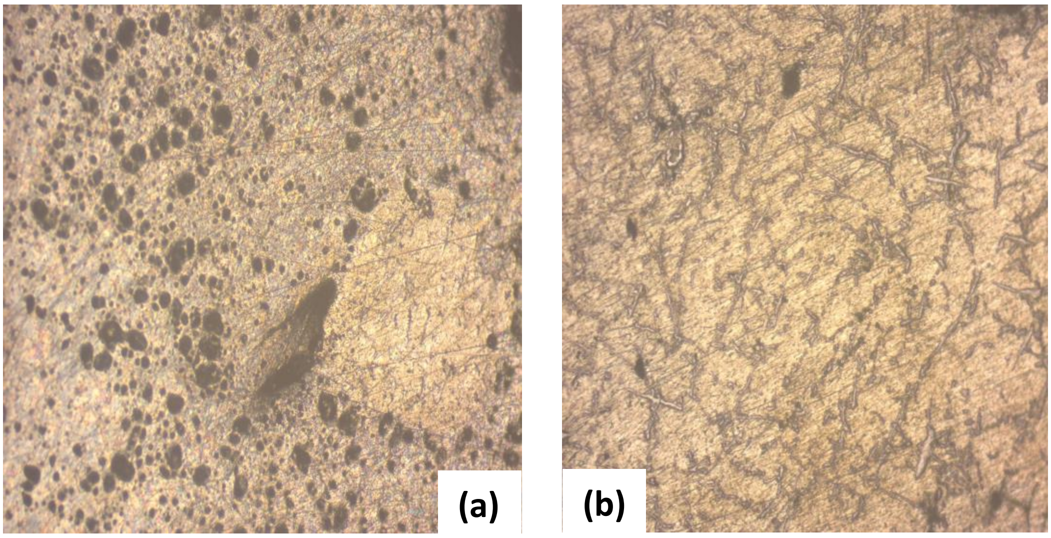
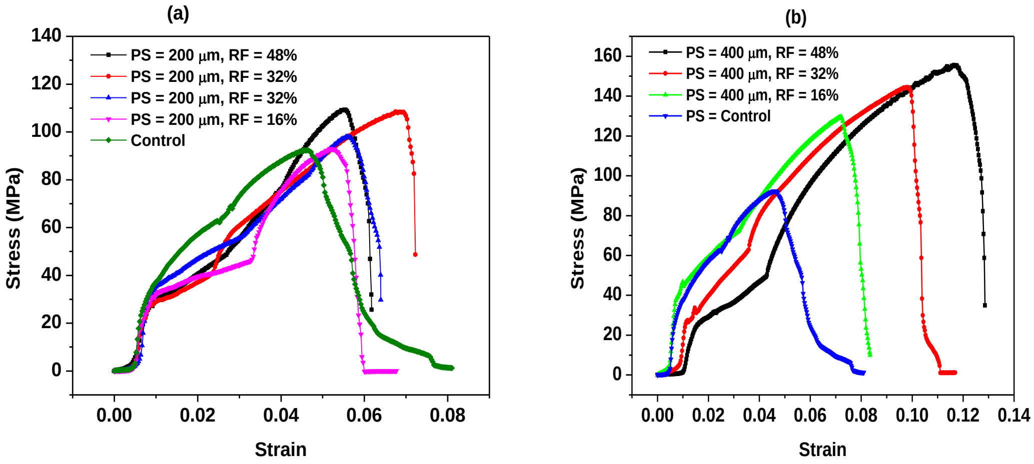


Figure 3. Optical Microstructure of (a) Unalloyed Aluminium (b) Aluminium Reinforced with 16wt.% of 600µm Size Snailshell Particles. The Magnification is 200

3.2. Tensile Strength and Hardness

The stress–strain curves for most of the samples (Figure 4) showed that the ultimate tensile stress increases with increased weight fraction and particle size. The tensile strengths and the hardness for the experimental runs are shown in Table 2. The reported values of the hardness are the averages of 18 trials. Analysis of Variance (ANOVA) was conducted on the tensile strength and hardness based on data presented in Table 2. A simple model containing linear, quadratic and interactive relationship was utilized for the outputs (Eq. 1 and Eq. 2). ANOVA results (Table 3) indicate that linear (A and B) and interactive (AxB) components are significant at 5% confidence limit. The quadratic relations are, however, not significant.



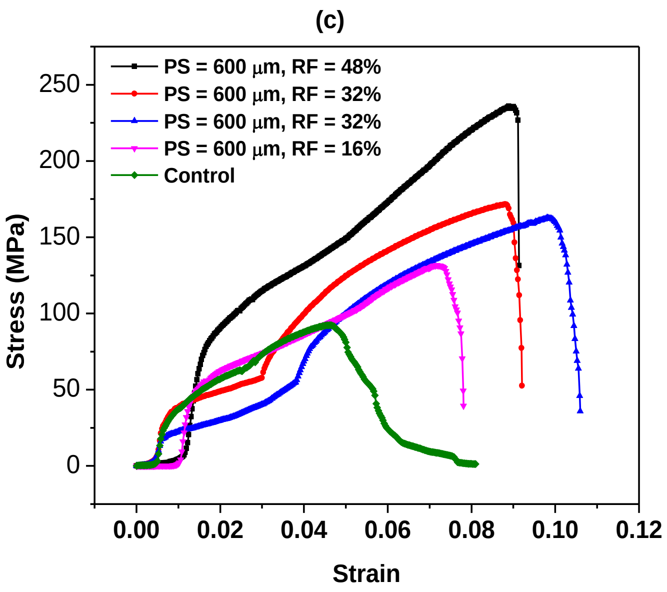


Figure 4. Stress-Strain Curves for Aluminium Composites at 16, 32 and 48 wt.% with Uncarbonized Snailshell Particles of (a) 200 μm (b) 400 μm and (c) 600μm

Table 2. Experimental Results based on Box Behnken Design

Experimental Run	A: Reinforcement (%wt)	B: Particle size (μm)	Hardness (HRF)	Tensile strength (MPa)
1	32	400	42.8	143.0
2	32	600	47.9	171.7
3	16	400	38.0	124.7
4	32	600	47.9	162.7
5	48	200	37.7	109.3
6	32	400	41.9	131.8
7	48	400	46.3	155.6
8	32	200	37.0	108.4
9	48	600	48.3	236.0
10	16	400	37.9	114.3
11	32	400	41.1	130.2
12	32	200	34.9	97.9
13	48	400	46.3	144.4
14	16	200	32.8	93.0
15	32	400	40.9	129.5
16	16	600	47.4	157.7
17	32	400	38.8	124.9

Table 3. ANOVA Table for Tensile Strength

Source	Sum of squares	Degree of freedom	Mean square	F-value	Prob > F
Model	17359.58	5	3471.92	32.88	< 0.0001 (S)
RF	3026.42	1	3026.42	28.66	0.0002 (S)
PS	12760.03	1	12760.03	120.83	< 0.0001 (S)
RF^2	274.24	1	274.24	2.60	0.1354 (NS)

PS^2	303.92	1	303.92	2.88	0.1179 (NS)
RF*PS	961.00	1	961.00	9.10	0.0117 (S)
Residual	1161.60		105.60		
Lack of fit	768.31		256.10	5.21	0.0276

RF is reinforcement (wt. %) and PS is the particle size (µm); S indicates 'significant', NS is 'non significant'

Statistical models for tensile strength (Eq. 1) and hardness (Eq. 2) have respective coefficients of regression R^2 of 0.94 and 0.93, indicating that the data are accurately fitted.

$$TS = 138.97237 - 2.73668 * \mathrm{RF} - 0.12500 * \mathrm{PS} + 0.031481 * RF^2 + 0.0002 * \mathrm{PS}^2 + 0.004 * \mathrm{RF} * \mathrm{PS} \quad (\mathbf{R^2 = 0.94}) \tag{1}$$

$$\mathrm{H} = 21.58947 + 0.21032 * \mathrm{RF} + 0.037451 * \mathrm{PS} + 0.00141 * \mathrm{RF}^2 + 0.00000404 * \mathrm{PS}^2 - 0.000312 * \mathrm{RF} * \mathrm{PS} \quad (\mathbf{R^2 = 0.93}) \tag{2}$$

TS is the tensile strength (MPa) and H is the hardness (HRF)

3.3. Parametric Study

To further demonstrate the robustness of the statistical models,we carried out trend analyses using Eqs. (1) and (2) by comparing the model results with the experimental values. The influences of weight fraction and particle size of the reinforcement on the tensile strength and hardness of the composites are depicted in Figure 5. The fraction of the reinforcement was varied between 15 and 55 wt.% while the particle sizes were as used in the experiments. For each of the particle size, the tensile strength and hardness were computed for the range of the reinforcement particle size. It is observed that the model results follow the similar trend as those of the experiments indicating that the model performs excellently (Figure 5).

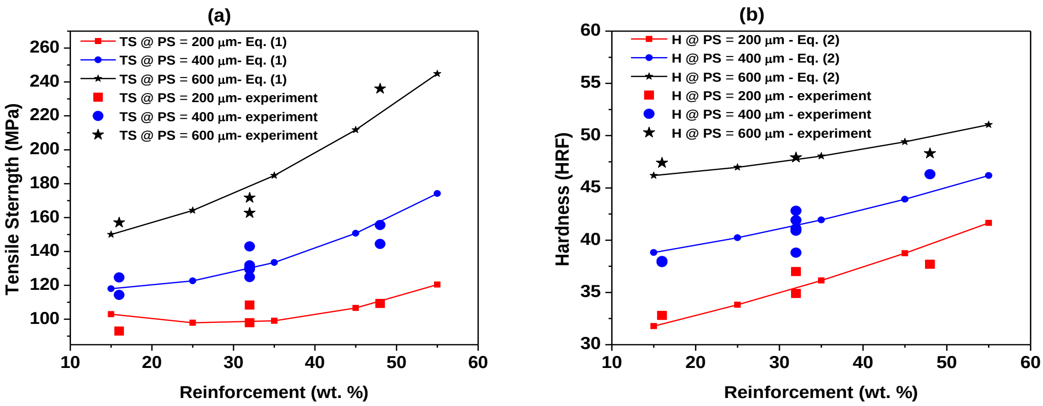


Figure 5. Variation of (a) Tensile Strength and (b) Hardness with Weight Fraction of Reinforcement based on Eq. (1) and Eq. (2). Experimental Results are Included

Tensile strength increased with increased weight fraction of snailshell particles (Figure 5a). For example, at 600 µm particle size, the tensile strength increased from 92.4 MPa at 0 wt.% to 236 MPa at 48 wt.%. This increase is attributed to uniform distribution of snailshell particles in the ductile aluminium matrix [14]. According to previous studies [17-18], reinforcements enhanced tensile strength by matrix strengthening. Reduction in composite grain size generates high dislocation density in the matrix as a result of the difference in coefficients of thermal expansion between the matrix and reinforcement. In addition, wettability ensure good bonding between the matrix and reinforcement [4] which significantly favours enhancement of the ultimate tensile strength of the composite.

Similarly, the hardness increases as the weight fraction of snailshell particles increases. This increment is attributed to an increase of the weight fraction of hard phase of the snailshell particles. The hardness of the snail shell particles is due to the presence of $CaCO_3$, C and SiO_2 of the chemical made up of the particles [16]. Bigger particles offer less grain boundaries, and thus higher fraction of the harder component. This subsequently improves hardness and strength.

4. Conclusions

Snailshell particles were successfully incorporated in aluminum alloy by using the stir casting technique. The microstructural analysis showed that the particles were uniformly distributed. The uniform distribution of the particles is largely responsible for the enhancement of tensile strength and hardness of the composite. Addition of snailshell particles reinforcement to aluminum alloy increased the tensile strength and the hardness value of the Al-snailshell particulate composites. This could potentially lead to the production of low cost aluminum composites with improved hardness and strength. These composites can find applications in automotive components like pistons, cylinder liners and connecting rods as well as applications where lightweight materials are required with good stiffness and strength.

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