Characterization of Al-Mg-Si Alloy Reinforced with Optimum Palm Kernel Shell Ash (PKSA) Particle and its Consequence on the Dynamic Properties for Aerospace Application

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Abstract

Nowadays, the demand for naturally and locally sourced materials for usage in automobile and aerospace have been on the increase due to high usage and population increase. In this view, this research is focused on investigating aluminium metal matrix composite materials with the aim of studying the optimum composition effect of Al-Mg-Si alloy reinforced with Palm Kernel Shell Ash (PKSA) particle on static and dynamic properties. Powder methodology was used to manufacture the developed composites. The SEM result showed that the recrystallization during ball milling of the mixture powders characterized the accumulation of higher dislocation density and the presence of harder phases in the PKSA which contributed to their improved thermal properties. Furthermore, the modulus of rupture of the developed Al-Mg-Si-PKSA matrix composites was effectively increased, and it can be drawn that sample C4 (6:94 wt%) has optimized properties. In this study, the storage modulus (E'), loss modulus (E''), damping factor ($\tan \delta$) were determined based on the Dynamic Mechanical Thermal Analysis (DMTA) of the developed composites. It was established that the glass transition temperature (T_g) increased with frequency and amplitude. The result of this research also revealed the optimum percentage composition of 6 wt% PKSA on Al-Mg-Si powder is suitable for research aerospace applications.

1. Introduction

In recent years composites have been of great importance in the automobile and aerospace industries where weight and strength are considered of utmost importance. In most manufacturing industries where components and parts are fabricated, concerns are raised for researchers to focus more on material production with preferences to local content partial replacement materials in the manufacturing of components, accessories and parts. The enhanced mechanical properties of composites established using industrial agro-wastes such as fly ash, palm oil clinkers, palm oil fuel ash, and palm kernel ash, especially with low cost and high strength to weight ratio, make them potentially useful for industrial, aerospace and automotive applications [1–5]. A previous study employed the use of rice husk ash which is readily available and relatively cheap; consequently, the result of the study showed that the composites created utilizing rice husk ash for fortification can be utilized importantly in developing automotive parts such as cylinder liners, pistons, connecting rods, etc. [6]. The hard phases such as SiO_2 , Fe_2O_3 , Al_2O_3 and Cr_2O_3 present in agro-wastes [7–10] contribute to the enhancement of the hardness, fracture toughness and tensile strength of the established composites which makes them appropriate for the intended applications. Other studies also showed that the metal-matrix composites developed using agro-wastes for reinforcement have shown decreasing trend in the density and an enhancement in the mechanical properties, these results further strengthen the notion that such developed composites can be used in the fabrication of engineering components [11–13, 16, 17]. In this study, however, the consequence of reinforcing Al-Mg-Si Alloy with Palm Kernel Shell Ash (PKSA) is investigated with respect to the resulting dynamic mechanical properties of the composite and its suitability for aerospace application.

2. Materials And Methods

2.1 Materials

Pure Aluminium, Magnesium, Silicon, Copper, Manganese and Chromium powders which were purchased from Shanghai Worldyang Chemical Co., Ltd. (ISO9001:2008) Shanghai, China were used as the basic Aluminium 6066 alloy source. In this respect, information on the physical and chemical properties of the powders was established.

Fresh palm kernel shells (PKS) were obtained from a palm oil processing firm in Ikire, Osun State, South-West, Nigeria. However, the sample used was a mixture of shells from Dura and Pisifera species since the varieties are not habitually sorted during the processing.

2.2 Methods

Materials Preparation

The typical alloying elements of 6000 series aluminium AA6066 constitutes silicon, magnesium, copper, manganese and chromium were used for the formulation as shown in Table 1. The percentage distribution adopted for the formulation of the experiment is presented in Table 2.

The mixture of the combined species was sun-dried to a considerable dryness, washed and thereafter crushed with beater crushers to enable particle production. The particle was further ground in a two-roll mill to aid particle sizing to ensure homogeneity. These processes are vital as it permits the hydrophilic properties regulation and moisture composition percentage to be established. This process is a derivative of a similar method employed in the studies of Alaneme, *et al.*, [9, 19].

Table 1
Chemical Composition of Aluminium Alloy AA6066

Element	Si	Mg	Cu	Mn	Cr	Al
Composition (%)	0.9–1.8	0.8–1.4	0.7–1.2	0.6–1.1	0.4	Bal

Table 2
Formulated Composition of Aluminium Alloy AA6066

Element	Si	Mg	Cu	Mn	Cr	Al
Composition (%)	1.20	1.10	1.0	0.7	0.4	Bal

Development Process

The development process of the Al-Mg-Si-PKSA composite using powder metallurgy is as shown in Fig. 1.

2.3 SEM Analysis

The morphology of the samples was carried out on an ultra-high vacuum and high-resolution scanning electron microscope (SEM) operated at 16.0 kV. The samples were arranged by gold sputtering with the surface of the samples using a low deposition rate.

2.4 Static Mechanical Tests

To investigate the effect of reinforcement of palm kernel shell ash particle with aluminium alloy on the static mechanical properties, the flexural strength was prepared using third-point loading and spans length in accordance to standard ASTM B925-08 at room temperature using the Dynamic Mechanical Thermal Analysis (DMTA) and Motorized Automatic Recording Tensometer as shown in Plate 1 (a) and (b). The samples were prepared following the standard measurement as shown in Plate 2.

The sample size for MOR tests was 400 mm by 100 mm by 16 mm according to the BS 5669 standard. The samples were subjected to a cross-head speed of 5mm/min and a loading span of 384mm. The MOR was determined using Eq. (1).

$$\sigma = \frac{3FL}{2bd^2} \quad (1)$$

Where F is the load at the fracture point, L is the length of the support span, b is the width of the sample, and d is the thickness of the sample.

2.5 Damping Measurements

Materials that exhibit both viscous and elastic behaviour are classified as viscoelastic materials. Properties of these materials are considered to be very important in providing the interfacial bonding between the alloy and reinforcement (PKSA). Hence, properties such as the storage modulus E' , loss modulus E'' and damping factor ($\tan \delta$) were evaluated. The storage modulus measures the stored energy in the material representing the elastic portion while the loss modulus the energy dissipated as heat denotes the viscous portion whereas the ratio of the later and former is classified as loss factor ($\tan \delta$). $\tan \delta$ is ultimately an indication of the effectiveness of the material's damping capabilities whereby effectively accomplishing energy absorption and dispersion of the material more effectively.

To enable the development, particle distribution, frequency on storage modulus and loss factor were conducted using the dynamic mechanical thermal analyzer. The experiments were carried out at mode 1 Hz, 5 Hz and 10 Hz frequencies under a dynamic load of 2000×10^{-3} N and at a temperature range: 29.0°C/6.0 (K/min)/200.0°C with the DMTA machine shown in Plate 1(a).

3. Results And Discussions

3.1 SEM Analysis

The microstructural characterization of the samples (C1-C7) is given in Fig. 2. The result shows the SEM image of sample C1 being the control (unreinforced) and it was observed that there exist mixtures of individual particles and necking in the sample, which could be a result of non-homogeneity. In contrast, on the addition of reinforcement as seen from Fig. 2 for samples C2 to C4, the SEM images revealed that there were many networks of coalesced or necked particles but individual particles are hardly found, which in turn resulted in a high degree of densification ratio for these compositions. However, on further addition of reinforcement as shown in Fig. 2 for samples C5 to C7, the development of a highly bonded solid can be noticed which can be responsible for the reduction in the mechanical properties of the samples. Also, due to the increase in the reinforcement percentage from C5 to C7, the presence of silicon carbide and graphite from the reinforcement increases their presence in the composite which is responsible for the segregation of the particles within samples C5 to C7. This result is in agreement with the findings of Oyedele et al. [20] who discovered that on the addition of reinforcement to Aluminium alloy beyond certain limits, highly bonded solids begin to develop which results in a decrease in the mechanical properties of the composites.

3.2 Static Mechanical Properties

The response of the samples to flexural stress at the peak is shown in Fig. 3. The result showed that sample C4 has the highest modulus of rupture (MOR) value of 69.25 MPa, followed by C5 with 68.28 MPa. In comparison with the control sample (C1) with MOR of 50.40 MPa, samples C4 and C5 recorded an increase in MOR with 37.4% and 35.5% respectively. It is also interesting to note that all other reinforced samples (C2, C3, C6 and C7) showed improved properties in terms of MOR value. From the results, C4 has the most excellent flexural stress property with the composition 6:94 wt% of treated palm kernel ash added to the sample. Hence, it has been established that the primary benefit of particle reinforcement arises from the particle-bridging effect which depends on the material properties of the reinforcement, matrix, and the interfacial transition. This benefit is vital to enhance the matrix and bonding strength of the material.

3.3 Dynamic Mechanical Properties

The results of thermal tests were obtained using Dynamic Mechanical Analyzer DMA242E (Artemis) to ascertain the dynamic loading on the samples. The experiments were conducted at varying frequencies between temperatures ranging from 0°C to 200°C.

Effect of Frequency Variations on Storage Modulus

The three-point bending mode experiment was performed in a DMTA machine using the standard conditions. The storage modulus E' values result for the varying frequencies (1, 5 and 10 Hz) are presented for C1 (control) and the reinforced samples C2, C3, C4, C5, C6 and C7 as shown in Fig. 4.

Generally, from the behaviour of metal composites [C1-C7], it can be observed in all DMTAs results, eventually, storage modulus decreases with temperature. It can also be observed that this decrease was even more rapid as the material approached its glassy region due to its interaction between the matrix

and reinforcement. In this region, the highest values of storage moduli were obtained by all composite samples at 10 Hz frequencies except for sample C4 that showed double endothermic peaks. On the other hand, the lowest values were shown at 1 Hz frequencies in all the composite samples.

Furthermore, sample material with 6 wt% PKSA (sample C4) shows a unique result as the storage modulus decreased and increased sharply before and after the glass transition T_g . An indication of such a reaction between the material's shows softening due to temperature change. The result also showed that beyond 6 wt% PKSA (the optimum weight ratio) there is a sudden decrease in storage modulus value as temperature increases due to increment beyond the optimum ratio and improper adhesion between the matrix and reinforcement [14]. In this region, addition of reinforcement percentage increases the values of storage moduli due to increase in frequencies which follows this order: $C4 > C5 > C6 > C3 > C2 > C1 > C7$.

In the rubbery region, values of storage moduli increase with frequency increase in all the samples at 10 Hz frequencies. Similar reports have shown that storage modulus increase with an increase in frequency [15]. In this region, increase in values of storage moduli due to increase in frequencies follows the order: $C4 > C3 > C6 > C5 > C2 > C1 > C7$.

Effect of Frequency Variations of Loss Modulus

The loss modulus is presented in Fig. 5. This result shows the behaviour of the control sample in comparison with the reinforced samples as a function of temperature at 1 Hz frequencies. The control sample C1, decreased with no peaks as temperature increases while the reinforced samples show peaks and gradually decreased in samples C2, C3, C4, C5, C6 and C7. Similar results show significant variation in frequencies in storage moduli is also reported in loss moduli.

It was observed that loss modulus increased slightly up to a certain temperature and thereafter, suddenly decreased with an increase in temperature having the highest frequency recorded on 10 Hz on all the samples. The onset points of most reinforced samples provided higher storage modulus and peak points of loss moduli before glass transition T_g . The highest peaks of loss moduli curves were shown for composite sample C4 at 10 Hz frequencies followed by C3, C6 C5, C2, C1 and C7. These increases of loss moduli values could be due to an increase in molecular activities due to the increase in frequency [15].

Tan Delta

From the Tan Delta result obtained for the samples, it was seen from Fig. 6 that there is a trend in damping capacity with a change in temperature for all the samples at all test frequencies. The damping capacity of all the samples was observed to increase with temperature in the range of 80–120 °C. The highest peaks of damping were found at 1.0 Hz frequencies in all samples, these could be attributed to the inherent damping properties of aluminium and the reinforcement. Furthermore, the highest thermal stability was obtained at lower frequencies 1.0 Hz, whereas the lowest thermal stability was obtained at higher frequencies 10 Hz in all samples.

Furthermore, the higher damping capacity observed at low frequencies can be attributed to the reciprocating motion of dislocations which tends to dissipate more energy. Normally, dislocation density decreased with increasing temperature, which means that the contribution of the dislocation induced damping mechanism. Similarly, at a higher temperature, the interfacial bonding strength between the matrix and the reinforcement phase was weakened because the aluminium became less stiff and increased the interface slip distance [18].

Table 3 shows the maximum loss factor and glass transition temperature for the samples at the various frequencies. The result showed that the lowest maximum loss factor is observed from sample C4 and is found to change with variation in frequency from 1–10 Hz. This is established by the fact that at an increase in the frequency of vibration, the composite tends to lose energy within the glassy region. In addition, the loss factor curve for sample C4 shows double peaks and this can be achieved due to its micro-mechanical properties unlike the plots of others which reach a maximum value at the transition region and start to decrease.

Table 3
Maximum Loss Factor and Maximum Glass Transition Temperature of
Al-Mg-Si/PKSA Composite at 1.0 Hz, 5.0 Hz and 10 Hz Frequencies.

Specimen	Maximum Peak ($\tan \delta$) 10^{-3}			Maximum Tg (°C)		
	1 Hz	5 Hz	10 Hz	1 Hz	5 Hz	10 Hz
Sample C1	0.077	0.079	0.075	33.2	31.3	30.9
Sample C2	0.076	0.068	0.073	59.1	68.5	57.6
Sample C3	0.145	0.136	0.136	97.2	98.9	98.9
Sample C4	0.059	0.055	0.058	103.0	98.3	98.3
Sample C5	0.065	0.063	0.066	44.2	42.4	51.2
Sample C6	0.073	0.071	0.072	20.7	30.3	30.3
Sample C7	0.102	0.095	0.094	80.1	82.1	82.3

4. Conclusion

The SEM result of this study established that the recrystallization during ball milling of the powdered composition characterized the accumulation of higher dislocation density and the presence of harder phases in the PKSA which contributed to their improved properties. Experimentation on static and dynamic mechanical characterization of Al-Mg-Si alloy reinforced PKSA particles was carried out and from the results obtained it can be established that the optimum weight percentage (6.0 wt % PKSA) posse's substantial properties when compared with the unreinforced (control) sample and also found to have an improved storage modulus, loss modulus and damping behaviour. Furthermore, it was also

established that the storage modulus glassy region of particle reinforced has been affected by frequency as shown by the increase in frequency from 1.0 to 10 Hz. The highest peaks of damping were found at 1 Hz frequencies and lower damping were found at 10 Hz frequencies. However, glass transition/thermal stability was found to reduce with increase frequencies within 60 °C and 95 °C across all frequencies. The trend of decrease in damping with weight fraction of reinforcement for sample C4, having the optimum thermal properties due to its promising load-bearing capacity is studied. These results revealed that the developed composite, especially sample C4 can be applied in many engineering applications such as aerospace and automobile applications.

Declarations

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Conflicts of Interest/Competing Interests: Not applicable

Availability of data and Material: Available on request

Code Availability: Not applicable

References

1. Lancaster L, Lung MH, Sujan D (2013, January) Utilization of agro-industrial waste in metal matrix composites: towards sustainability. In *Proceedings of World Academy of Science, Engineering and Technology* (No. 73, p. 1136). World Academy of Science, Engineering and Technology (WASET)
2. Bodunrin MO, Alaneme KK, Chown LH (2015) Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *Journal of materials research technology* 4(4):434–445. doi:10.1016/j.jmrt.2015.05.003
3. Teuber L, Osburg VS, Toporowski W, Militz H, Krause A (2016) Wood polymer composites and their contribution to cascading utilisation. *J Clean Prod* 110:9–15. doi:10.1016/j.jclepro.2015.04.009
4. Ikumapayi OM, Akinlabi ET (2018) Composition, characteristics and socioeconomic benefits of palm kernel shell exploitation-an overview. *J Environ Sci Technol* 11(6):1–13
5. Prakash R, Thenmozhi R, Raman SN, Subramanian C (2020) Fibre-reinforced concrete containing waste coconut shell aggregate, fly ash and polypropylene fibre. *Revista Facultad de Ingenieria Universidad de Antioquia*, (94), doi:10.17533/10.17533/udea.redin.20190403
6. Arora G, Sharma S (2017) A review on monolithic and hybrid metal–matrix composites reinforced with industrial-agro wastes. *Journal of the Brazilian Society of Mechanical Sciences Engineering* 39(11):4819–4835. doi:10.1007/s40430-017-0910-x
7. Onyechi PC, Asiegbu KO, Igwegbe CA, Nwosu MC (2015) Effect of particle size on the mechanical properties of periwinkle shell reinforced polyester composite (PRPC). *International Journal of Scientific Engineering Research* 6(3):1064–1096

8. Iorshagher SA (2016) *Effect of Partial Replacement of Cement With Marble Dust And Groundnut Husk Ash On Concrete* (Doctoral Dissertation, University Of Agriculture Makurdi)
9. Alaneme KK, Bodunrin MO, Awe AA (2018) Microstructure, mechanical and fracture properties of groundnut shell ash and silicon carbide dispersion strengthened aluminium matrix composites. *Journal of King Saud University-Engineering Sciences* 30(1):96–103. doi:10.1016/j.jksues.2016.01.001
10. Prakash R, Thenmozhi R, Raman SN, Subramanian C, Divyah N (2021) An investigation of key mechanical and durability properties of coconut shell concrete with partial replacement of fly ash. *Structural Concrete* 22(Suppl. 1):E985–E996. doi:10.1002/suco.201900162
11. Kolawole MY, Aweda A, Abdulkareem S (2017) Archachatina marginata bio-shells as reinforcement material in metal matrix composites. *International Journal of Automotive Mechanical Engineering*, 14(1), doi:10.15282/ijame.14.1.2017.18.0328
12. Birhan G (2018) *The Assessment of Peanut shell and Chat stem as Alternative Energy Source for Cement Industries* (Doctoral dissertation, AAU)
13. Usman AM, Raji A, Hassan MA, Waziri NH (2014) A comparative study on the properties of Al-7% Si-Rice husk ash and Al-7% Si-Bagasse ash composites produced by stir casting. *The International Journal of Engineering Science* 3(8):1–7
14. Samal SK, Mohanty S, Nayak SK (2009) Banana/glass fibre-reinforced polypropylene hybrid composites: Fabrication and performance evaluation. *Polymer-Plastics Technology Engineering* 48(4):397–414
15. Liu MH, Li R, Wang G, Hou ZY, Huang B (2016) Morphology and dynamic mechanical properties of long glass fibre-reinforced polyamide 6 composites. *J Therm Anal Calorim* 126(3):1281–1288
16. Wang KY, Zhao RD, Wu FF, Wu XF, Chen MH, Xiang J, Chen SH (2020) Improving microstructure and mechanical properties of hypoeutectic Al-Mg₂Si alloy by Gd addition. *J Alloy Compd* 813:152178
17. Cai Q, Mendis CL, Chang IT, Fan Z (2020) Microstructure evolution and mechanical properties of new die-cast Al-Si-Mg-Mn alloys. *Materials Design* 187:108394
18. Cakmak E, Gussev MN, Sridharan N, Seren MH, An K, Wang H, Terrani KA (2020) Micromechanical and microstructure analysis of strain-induced phenomena in ultrasonic additively-manufactured Al-6061 alloy. *Materials Science Engineering: A* 770:138533
19. Alaneme KK, Adewale TM, Olubambi PA (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 Technology* 3(1):9–16
20. Oyedele EO, Dauda M, Yaro SA, Abdulwahab M (2021) The effect of palm kernel shell ash reinforcement on microstructure and mechanical properties of Al-Mg-Si metal-matrix composites. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 09544062211014535

Plate1 and Plate2 are only available as a download in Supplemental Files section.

Figures

Figure 1

Development Process of Al-Mg-Si/PKSA by Powder Metallurgy

Figure 2

SEM Micrograph of C1 (Control), C2, C3, C4, C5, C6 and C7 At x 750 Magnifications

Figure 3

Modulus of Rupture (MOR) against the Samples type

Figure 4

Variation of storage modulus with respect to temperature of palm kernel shell ash/Al-Mg-Si alloy composites at 1 Hz, 5Hz and 10 Hz frequency

Figure 5

Variation of loss modulus with respect to temperature of palm kernel shell ash/Al-Mg-Si alloy composites at 1 Hz, 5Hz and 10 Hz frequency

Figure 6

Variation of tan delta with respect to the temperature of palm kernel shell ash/Al-Mg-Si alloy composites at 1 Hz, 5Hz and 10 Hz frequency

Supplementary Files

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