
INFLUENCE OF T6-AGING TREATMENT ON SELECTED MECHANICAL PROPERTIES OF ALUMINIUM ALLOY A356/MELON HUSK ASH NANOCOMPOSITE

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ABSTRACT

Aluminum matrix nanocomposites are gaining prominence in automobile manufacturing due to their competitive properties. The present study explores the effect of T6-aging treatment on the selected mechanical properties of a novel nanocomposite, namely Aluminium A356 reinforced with melon husk ash nanoparticles. Melon husk ash (MHA) nanoparticles, produced from an abundant Nigerian agro-waste—Egusi melon (*Citrullus colocynthis* L.) husks—were used to reinforce A356 aluminium alloy through a low-frequency vibration-assisted stir casting technique. Samples of the cast nanocomposite and the unreinforced alloy were subjected to T6-aging heat treatment, after which hardness and tensile properties were determined using standard test procedures. X-ray diffraction (XRD) and optical microscopy (OPM) were used to study the microstructure of the samples. XRD patterns of the nanocomposite samples revealed the presence of α -Al, Si, β -Al₅FeSi, Mg₂Si, and SiO₂, while optical micrographs revealed a refined microstructure comprising primary α -Al dendrites, acicular Si, and a relatively even distribution of nanoparticles within the matrix of the heat-treated nanocomposite samples. Results of the mechanical tests showed that the T6-heat-treated nanocomposite exhibited improved properties over both the as-cast nanocomposite and the unreinforced samples. The tensile strength of the heat-treated nanocomposite (180.57 MPa) represented an improvement of 24.87% over the as-cast nanocomposite and 53.42% over the as-cast unreinforced sample. The ductility of the heat-treated nanocomposite (6.63%) represented a 22% improvement over the as-cast nanocomposite and a 32% improvement over the as-cast alloy. Meanwhile, the hardness value of the heat-treated nanocomposite (127.14 HV) represented an improvement of 0.9% over the as-cast nanocomposite and 55% over the as-cast alloy. In summary, the study demonstrates that MHA nanoparticles are a viable and effective reinforcement for aluminium matrix composites, and that T6-aging heat treatment offers a sustainable pathway for enhancing their mechanical properties.

Keywords: Melon husk ash; Aluminium matrix nanocomposite; Agro waste; Mechanical properties; T6 heat treatment

1. INTRODUCTION

Metal matrix composites (MMCs) are an important class of engineering materials with attractive properties and widely used in aerospace and automotive applications (Azimi *et al.*, 2021). Although conventional composites (reinforced micron-sized particulates) may generally exhibit superior performance to their matrix alloys, they have significant drawbacks, including poor ductility and low fracture toughness compared to the bare alloys. To take care of these limitations, research focus has shifted towards developing metal matrix nanocomposites (i.e. metal matrices reinforced with nanoparticles), whereby the strength and ductility composites are improved simultaneously (Malaki *et al.*, 2020; Shayan *et al.*, 2020). This has opened the horizon for developing MMCs incorporating nanoparticles as reinforcing phase and amenable for several advanced applications.

A very common MMC used in automotive and other applications is aluminium matrix composite (AMC) owing to its lightweight and relatively good mechanical properties. The most commonly used aluminium alloys for aluminium matrix nanocomposites are those belonging to the Al-Si system owing to their high fluidity, low solidification shrinkage levels, corrosion resistance, etc. (Callegari *et al.*, 2023). When alloyed with Mg and/or Cu to form alloys like A356 Al-Mg-Si alloy, they become amenable to heat treatment, a thermal procedure used to improve their properties. The

procedure is the same for the alloys and composites developed from the alloys (Alam, 2014). The most common heat treatment procedure for modifying, particularly, the mechanical properties of Al-Si alloys containing Mg and/or Cu and their composites is the T6 age hardening or precipitation hardening (Tiwery *et al.*, 2018). The process, which basically enhances mechanical properties by forming fine precipitates that impede dislocation movement (Usman, 2026). In age-hardenable aluminium-based nanocomposites, the role of reinforcement nanoparticles during heat treatment includes accelerating the aging processes by creating more nucleation sites for precipitation within the α -Al and refining the microstructure by Zener pinning, i.e., restricting dendritic growth and altering the dendritic grain growth morphology (Guo *et al.*, 2018; Nithesh *et al.*, 2021).

Reinforcements used in fabricating the composite are mostly synthetic ceramic particulates of borides, oxides, carbides and nitrides (Samal *et al.*, 2020). However, industrial and agro waste-derived particulates are now becoming popular due to their relatively more economic viability and abundance (Parveez *et al.*, 2021); and to date, several agro-waste materials have been successfully incorporated into metal matrices to develop composites with competitive properties. However, most of the studies have been limited to micron size agro-based reinforcements, with limited studies on nano size agro-based reinforcements (Kelsey *et al.*, 2025).

Although nanoparticles-reinforced metal matrix composites exhibit superior properties, it is very difficult through stir casting (which is the most widely used and cost-effective composite fabrication route) to achieve uniform dispersion of the nanoparticles in the matrix, due to their large surface-to-volume (Shayan *et al.*, 2020), prompting researchers to implement modifications, such as application of ultrasonic vibrations to the molten mixture among several other methods, to improve the viability of the economic and simple casting process (Malaki *et al.*, 2019).

Melon husks (MHs) are agro wastes generated from processing of *Citrullus colocynthis* L. (commonly known in most parts of Nigeria as *Egusi* melon). Nigeria was ranked the highest producer of the crop in 2018 globally (Robert *et al.*, 2021). About a decade ago, a number of materials scientist have made attempts to convert melon husks to reinforcing materials for aluminium matrix composites. The studies have investigated the effect of melon husk ash particulates on mechanical and tribological properties of aluminium-based composites (Abdulwahab *et al.*, 2017; Suleiman *et al.*, 2018; Abolusoro *et al.*, 2025 & Usman *et al.*, 2026). However, most of the studies were limited to micron-sized particulates, and the effect of T6-heat treated was not investigated by the studies. The present study therefore investigates the effect of T6 heat treatment on the hardness and tensile properties of aluminium alloy A356/melon husk ash nanocomposite.

2. METHODOLOGY

2.1 Materials

The matrix is A356 aluminium alloy wheel scraps (AAWS), sourced from an automobile service center located at Zaria, Kaduna State of Nigeria. Chemical composition of the matrix alloy is shown in Table 1. The Si composition is slightly below that of a standard A356, consistent with previous studies on automobile aluminium alloy wheel (Song *et al.*, 2012). Melon husk ash nanoparticles (MHAnp) of average particle size 57.53 nm as reinforcement in this study was synthesized through thermal treatment and mechanical milling. Details of the synthesis route and characterization of the reinforcement (see Figures 1a &b) are reported in another study (Usman, 2026). Chemical composition of the MHAnp determined using X-ray fluorescence spectroscopy shows it is composed of SiO₂ as the constituent present in the largest amount, as shown in Table 2.



Figure 1: (a) Melon husks and (b) Melon husk ash

Table 1: *Chemical composition of aluminium alloy wheel scraps (AAWS)*

Element	Weight %
Al	91.87
Si	6.22
Mg	0.33
Cu	0.02
Fe	0.27
Mn	0.03
Sr	0.01
Others	Balance

Table 2: *Chemical composition of melon husk ash nanoparticles (MHAnp)*

Composition	Weight %
SiO ₂	39.50
K ₂ O	8.23
Al ₂ O ₃	8.44
MgO	6.53
CaO	7.66
P ₂ O ₅	15.00
Fe ₂ O ₃	6.09
SO ₃	1.70
Na ₂ O	1.75
SnO ₂	1.89
TiO ₂	0.92
ZnO	3.90

2.2 Fabrication of A356/MHAnp Samples

Al-Mg-Si alloy matrix composites reinforced with 3.5 vol. % melon husk ash nanoparticles (MHAnp) was produced by stir-casting process. The nanocomposite was fabricated by charging 795g of aluminium alloy wheel scrap (AAWS) pieces into a graphite crucible, heating the charge to a temperature of 800°C and holding at the same temperature for a length of time sufficient for complete melting of the matrix alloy. The temperature of the melt was then lowered to 600°C where it was semi-solid and 3.5 vol. % of MHA nanoparticles (preheated at 350°C for 1 hour) added to it and the mixture stirred continuously at a speed of 400 rpm for 7 minutes. 4 wt. % Mg (with respect to the matrix alloy) wrapped in an Al foil was added to compensate for losses during melting and to improve wettability. The temperature of the melt was then raised to 750°C and the molten mixture agitated for 2 minutes by dipping a probe resonating at a frequency of 60Hz (power output: 150W; voltage: 220V) to improve

dispersion of the nanoparticles in the matrix before pouring into a prepared sand mold. A control sample of the unreinforced alloy was also produced for comparison of properties.

2.3 Heat Treatment

Cast composite samples were subjected to T6 heat treatment, which involved successive solution treatment and artificial aging. The unreinforced alloy and nanocomposite specimens were subjected to T6 aging treatment which entails solution treatment at 540°C for 6 hours followed by water quenching at room temperature, and a final step of artificial aging at 155°C for 5 hours in accordance with the study by Haskel *et al.* (2018) on A356 wheels. X-ray diffraction (XRD) analysis and optical microscopy were conducted to study phases and morphologies of the heat-treated specimens, respectively.

2.4 Characterization

Microstructural examination: To study the morphological features of the samples, samples of dimensions $\varnothing 15 \times 10$ mm were machined and polished using emery clothes meshed 300, 600, 800, 1200 and 2400, successively. Alumina suspension (0.05 μm) was then subsequently used for final polishing. Thereafter, the samples were submerged in Keller's reagent and etched for 30s. Subsequently, the samples were washed and dried for microstructural observation and capturing under an optical metallurgical microscope equipped with an inbuilt camera (Model No.: NJF:-12A). The microstructures were captured at a magnification of $\times 100$. The phases present in the samples were also studied using X-ray diffraction (XRD) analysis.

Tensile test: Tensile test was performed in accordance with ASTM E-8 standard on Electronic Universal Testing Machine (Model: WDW-100KN, S/No.: 190536). Three standard tensile test samples were machined from each cast sample and tested for tensile properties on the universal testing machine at a crosshead speed of 10cm/min. Average of three observations was recorded as tensile strength and percent elongation of the sample, as the case may be.

Hardness test: Hardness values of the samples were determined using a Vicker's micro-hardness tester (Model: MV1-PC, machine no: 07/2012-1329) in accordance with ASTM E-384 standard. Samples of dimensions $\varnothing 15 \times 10$ mm were prepared for the test. An average of three observations were taken from indentations at different points on a polished surface of each sample with a load of 0.3 Kgf at 15 seconds dwell time.

3. RESULTS AND DISCUSSION

3.1 XRD Patterns of the Samples

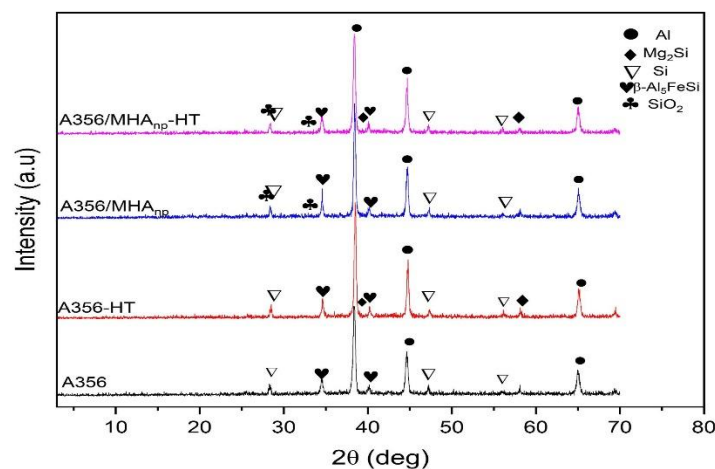


Figure 2: XRD patterns of the samples in as-cast and T6 heat-treated conditions

The XRD patterns of the alloy and nanocomposite samples, in both as-cast and T6-heat treated states, are depicted by Figure 2. The XRD patterns of the samples analysed using MDI Jade 6 software

show the presence of α -Al, Si, Mg, Mg_2Si , β - Al_5FeSi and SiO_2 . The XRD spectrum of A356 has the peaks (111) at $2\theta = 38.473^\circ$, (200) at $2\theta = 44.722^\circ$ and (220) at $2\theta = 65.099^\circ$ corresponding to Al (PDF card no. 99-005); the peaks (111) at $2\theta = 28.443^\circ$, (220) at $2\theta = 47.304^\circ$ and (311) at $2\theta = 56.124^\circ$ corresponding to Si (PDF card no. 99-0092); and minor peaks (111) at $2\theta = 34.594^\circ$ and (220) at $2\theta = 40.165^\circ$ corresponding to FeSi intermetallic compound, Al_5FeSi (PDF card no. 38-1397). Mg is also detected overlapping Si at $2\theta = 47.304^\circ$. These peaks are common to the other samples, except the peaks (211) at $2\theta = 28.794^\circ$ and (212) at $2\theta = 33.127^\circ$ corresponding to SiO_2 (PDF card no. 47-1300) present in A356/MHAnp and T6-heat treated A356/MHAnp, which could be from the agro-waste-derived reinforcement—melon husk ash nanoparticles. There are also other peaks present in the T6-heat treated alloy and nanocomposite samples, i.e., (220) at $2\theta = 40.121^\circ$ and (400) at $2\theta = 58.028^\circ$ corresponding to Mg_2Si precipitates (PDF card no. 35-0773). This finding is in agreement with previous studies on Al-Mg-Si alloys (Lakshmikanthan *et al.*, 2020).

3.2 Tensile Properties of the Samples

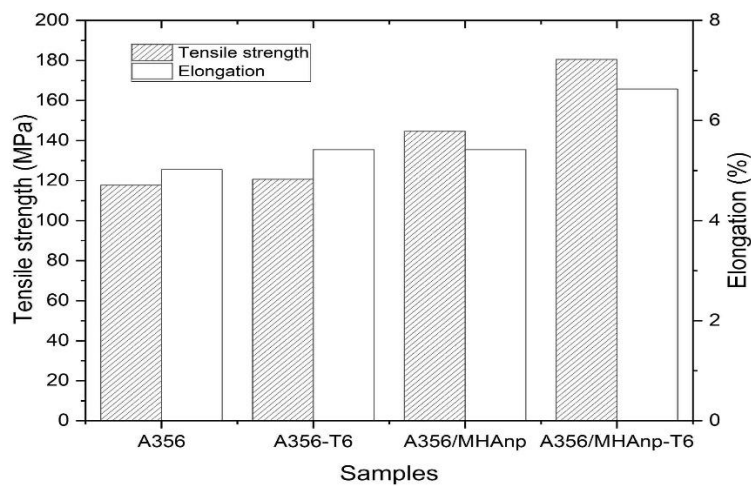


Figure 3: Tensile properties of samples in as-cast and heat-treated conditions

Figure 3 shows the tensile properties of the alloy and the nanocomposite samples, in the as-cast and heat-treated states. The tensile strength values are 117.70, 120.61, 144.60 and 180.57 MPa for A356, A356-T6, A356/MHAnp and A356/MHAnp-T6, respectively, and the percent elongation values are 5.02, 5.42, 5.42 and 6.63 for A356, A356-T6, A356/MHAnp and A356/MHAnp-T6, respectively. The improvement in tensile properties on addition of melon husk nanoparticles can be attributed to the resultant grain refinement and the action of the nanoparticles as barriers to dislocation movement, i.e. Orowan strengthening, thereby overcoming the traditional strength-ductility trade-off and simultaneously improving both properties (Singhal *et al.*, 2025). Similar observations were made by Li *et al.* (2019). Both alloy and nanocomposite samples in the T6-heat treated state also exhibited better tensile properties than the as-cast samples, an observation attributable to the strengthening effect of Mg_2Si precipitates in the heat-treated samples (Alam, 2014). The heat treatment condition may however require optimization as improvements in ductility are marginal.

3.3 Hardness of the Samples

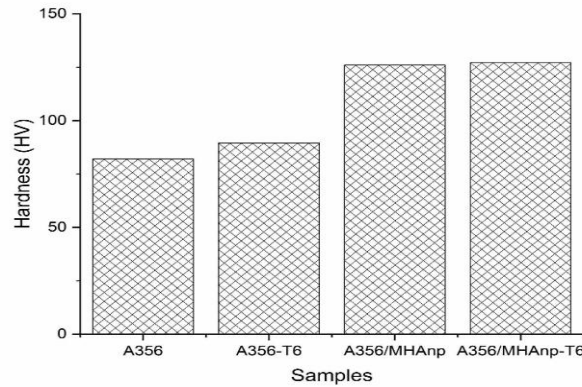


Figure 4: Hardness values of samples in as-cast and heat-treated conditions

Figure 4 shows the hardness values of the alloy and the nanocomposite samples, in the as-cast and heat-treated states. The micro hardness values are 82.00, 89.50, 126.00 and 127.14 HV for A356, A356-T6, A356/MHAnp and A356/MHAnp-T6, respectively. The results show significant enhancement in hardness by addition of melon husk nanoparticles to the alloy, underscoring the effectiveness of the nanoparticles in strengthening the Al alloy matrix. This observation can be attributed to increased dislocation density and grain refinement (Salur *et al.*, 2021). While noticeable improvement in hardness was observed for the alloy after heat treatment due to microstructural modifications and precipitation of the strengthening phase Mg_2Si , the improvement for the composite was negligible. The already high nanoparticle-induced hardness may have limited precipitation strengthening effects for the composites.

3.4 Microstructures of the Samples

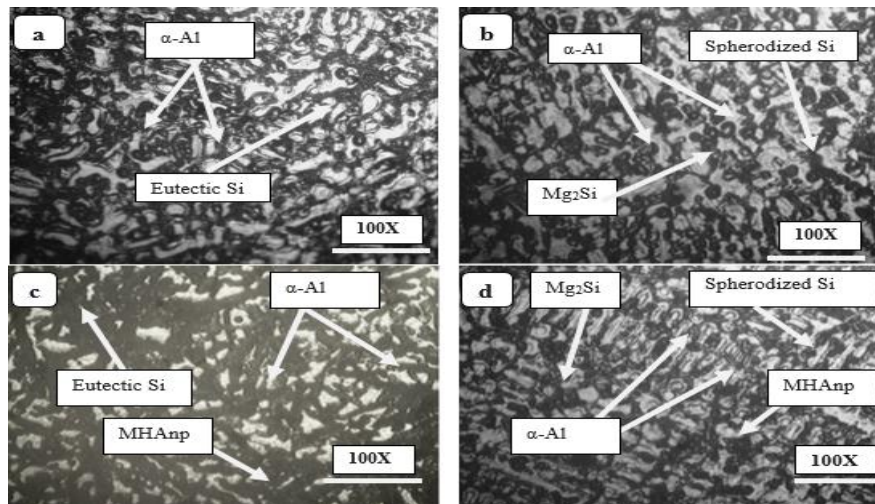


Plate I: Optical micrographs of (a) as-cast A356 alloy, (b) A356-T6 alloy, (c) as-cast A356/MHAnp composite and (d) A356/MHAnp-T6 composite; Etchant: Keller's reagent.

The microstructures of the alloy and nanocomposite samples, in both as-cast and T6-heat treated states, are depicted by the micrographs in Plates I (a-d).

The micrograph of the as-cast A356 sample in Plate I (a) shows dendritic structure of α -Al and acicular eutectic Si. In the micrograph of the T6-heat treated sample, in Plate I (b), spherodized Si and Mg_2Si precipitates are obvious in the matrix, which may have been responsible for the comparatively better mechanical properties of the heat treated sample. The micrograph in Plate I (c) depicts the microstructure of as-cast A356/MHAnp sample. The microstructure is finer than that of the alloy, which may have resulted from nanoparticles locking the grain boundaries and preventing excessive grain growth during cooling (Shayan *et al.*, 2020). The microstructure is made up of primary α -Al dendrites,

acicular Si and a relatively even distribution of nanoparticles. Some agglomeration are also noticeable at some spots, which may have been the cause for the marginal improvements in the tensile strength and ductility (Hoziefa *et al.*, 2016). The micrograph in Plate I (d) depicting the microstructure of the T6-heat treated nanocomposite sample shows the presence of continuous α -Al dendrite, spherodized Si, Mg_2Si precipitates and a relatively uniform distribution of MHAnp.

4. CONCLUSION

This study demonstrates that T6-aging heat treatment significantly enhances the mechanical properties of A356 aluminium alloy reinforced with melon husk ash (MHA) nanoparticles, based on the following key findings:

1. A356/MHAnp nanocomposites were successfully produced via low-frequency vibration-assisted stir casting, utilizing MHA nanoparticles derived from Nigerian Egusi melon husk agro-waste as a sustainable reinforcement.
2. XRD analysis confirmed the presence of α -Al, Si, β - Al_5FeSi , Mg_2Si , and SiO_2 phases, while optical microscopy revealed a refined microstructure with a relatively uniform nanoparticle distribution following heat treatment.
3. T6-aging improved tensile strength to 180.57 MPa, representing gains of 24.87% and 53.42% over the as-cast nanocomposite and unreinforced alloy, respectively.
4. Ductility of the heat-treated nanocomposite improved by 22% and 32% over the as-cast nanocomposite and alloy, respectively, indicating enhanced deformability alongside increased strength.
5. Hardness reached 127.14 HV, an improvement of 0.9% and 55% over the as-cast nanocomposite and unreinforced alloy, respectively.
6. Overall, MHA nanoparticles are an effective and sustainable reinforcement for A356 alloy, and T6-aging offers a practical pathway for optimizing its mechanical performance, positioning A356/MHAnp as a promising lightweight material for automotive applications.

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