Evaluation of impact and hardness properties of Al 6063-AgNPs composites produced by stir cast technique

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Abstract
The effect of silver nanoparticles (AgNPs) on the mechanical and microstructural properties of aluminium 6063 alloy was investigated. Aluminium 6063 matrix was homogeneously mixed with AgNPs impregnated with calcium carbonate at 2, 4 and 6% weight fractions. The mixture was used to produce refined samples through stir casting method. Measurement of impact strength and hardness property of the produced samples at ambient temperature was done by using Charpy impact and Brinell hardness testing machine in accordance with ASTM E23 and ASTM E384 respectively. The impact energy values (234-247 J) of all the samples with AgNPs/CaCO3 reinforcements were higher than the as-cast Al alloy (228 J) while the sample with 6% AgNp has the highest energy impact (247 J). Similarly, the hardness values (56.49-183.70 BHN) of all the samples with AgNPs/CaCO3 reinforcements were higher than the as-cast Al alloy (38.05 BHN) while the sample with 6% AgNPs has the highest (183.70 BHN). The magnitude of impact and hardness increased evidently with increase in percentage weight fraction of the AgNPs. The fracture images of the impact test samples revealed that the surface of AgNPs (CaCO3)-Al6063 composites were with dimples and there was a micro-void formation in CaCO3-Al6063 composite. The use of stir-casting technique influenced the homogeneity and microstructure of the AgNPs composites positively. The Al 6063-Ag nanocomposites possess better qualities in terms of impact energy and hardness, likewise can replace conventional aluminium alloy based on its performance.

Keywords: Al6063 alloy; Brinell hardness; calcium carbonate; impact strength; silver nanoparticles
1. Introduction

Aluminium metal, alloys and composites are becoming more relevant in engineering applications as a result of their excellent physical and mechanical properties [1]. The usage of aluminium alloy has gained serious attention in the area of automobile, aerospace and marine due to its higher strength, better resistance to corrosion, better ductility and light weight [2]. Its application in aerospace and marine industries is as a result of minimal density, increased strength, stiffness, resistance to fatigue and stable dimension at high temperature [3]. The adoption in metal matrix composites is also an emerging trend owing to its excellent mechanical properties. It has ability to solidify at a large varying temperature and as well adapted perfectly for treatment in the semi-solid state [4, 5]. Aluminium matrix composites are particularly influential due to best combination of strength, ductility, toughness and most especially can be process via conventional method [6].

Reinforcement type plays a key role in the property reliability of the metal matrix composites, especially aluminium matrix composite [6]. The reinforcement must not be a reactive type and should be steady in the specified temperature. The frequently used reinforcements are silicon carbide (SiC) and aluminium oxide (Al₂O₃) [6], resulting in increase in tensile strength, hardness and wear resistance when silicon carbide is used and likewise Al₂O₃ offers good compressive strength and wear resistance [6]. In the situation where the reinforcements are particles with nanometric sizes, the composite or alloy is known to be nanocomposites [7] which are more stable at medium temperature [8]. Alloying with silver nanoparticles (AgNPs) is gaining attention in the field of engineering owing to its uniqueness in optical, electrical and thermal properties as its being delivered into products ranging from photovoltaic to biological and chemical sensors [9, 10]. Emerging application areas of AgNPs are in antimicrobial coatings, textiles and biomedical devices [11].

Stir casting technique has been adopted for its commercial production due to its simplicity, flexibility in the control of matrix and most importantly, cost effectiveness [3]. It offers greater matrix reinforcement bonding than the other conventional methods due to the stirring action, couple with appropriate processing parameters [12]. Optimal mechanical property of the composite materials is a function of the level of homogeneity, which must be reasonably high [3]. The porosity level must also be minimal [13, 14]. Different studies by authors on the wear rate of the materials were as a result of the distance between the loading and sliding [15, 16]. The
sliding wear resistance of the composite was examined at different sliding speeds over different loading and distance levels. There is increase in wear behaviour as the loads and distances are increasing while the material exhibits less wear with increase in speed of sliding. Another study on the microhardness of composite of aluminium 7075 alloy with AgNPs by Flores-Campos et al. [17] shows that microhardness value increases with increasing AgNPs in relation with the aluminium alloy, both in the powder and extruded conditions. In this study, the effects of AgNPs impregnated with calcium carbonate on impact strength and hardness properties of aluminium 6063 alloy were examined in order to ascertain the responsiveness of the matrix to the varying weight fractions of reinforcement.

2. Materials and Methods

The materials considered in the study are AgNPs impregnated with calcium carbonate, incorporated into aluminium 6063 alloy as matrix. This type of alloy is good for production of lightweight metal castings [3]. Al 6063 was obtained as scrap aluminium profile sourced from some construction sites within Afe Babalola University, Ado-Ekiti, Nigeria. The percentage mass fraction of the compositions of Al6063 alloy is shown in Table 1. Silver nanoparticles of about 80 nm in size used for this study was synthesized using cobweb [18] and obtained from the Laboratory of Industrial Microbiology and Nanobiotechnology, Department of Pure and Applied Biology, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. Also, calcium carbonate was sourced locally from a supplier at Ado-Ekiti, Nigeria. Table 2 shows the property values of aluminium matrix and AgNPs. Figure 1 shows the average size distribution of silver nanoparticles measured with particle analyzer.

| Table 1. Chemical composition of Al 6063 (Mass Fraction %) |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Si   | Fe   | Cu    | Mn    | Mg    | Cr    | Zn    | Ti    | Al    |
| 0.86 | 0.19 | ≤0.01 | 0.04  | 0.51  | 0.01  | 0.01  | 0.008 | Bal.  |

Source: [3]
Table 2. Properties of Al6063 and AgNPs

| Material | Elastic Modulus (Gpa) | Density Kg/m³ | Poisson Ratio | Hardness (HB 500) | Tensile Strength (mPa) | Melting Point (°C) | Boiling Point (°C) |
|----------|----------------------|---------------|--------------|------------------|------------------------|-------------------|---------------------|
| Al 6063  | 70-80                | 2.7           | 0.33         | 95               | 310                    | 652               | 2519                |
| AgNPs    | 72-76                | 10.49         | 0.37         | 206              | 360                    | 962               | 2212                |

Source: [3]

Figure 1. Average size of the AgNPs

2.1 Sample Preparation

The sample preparation was divided into three stages, namely: impregnation AgNPs with CaCO₃, recycling of scrap aluminium profile and preparation of Al-AgNPs composite from Al6063 alloy.

2.1.1 Impregnation of AgNPs with CaCO₃

Exactly 95 ml of AgNPs was measured, mixed with 158 g of CaCO₃ thoroughly using Heidolph rzt 20121 automatic stirrer in a beaker at 1783 rpm into slurry form. The slurry was then sundried for 5 h for solidification, after which it was ground into powder using crucible, sieve through a 425 µm mesh to obtained even particle size distribution.
2.1.2 Recycling of Aluminium 6063 Scrap

The recycling of Al 6063 scraps followed the sequence described in Figure 3. The first step in the preparation of the scrap Al 6063 profiles include washing and drying in open air to remove stains and sand contaminants. Aluminium scrap is then weighed, packed into diesel fired crucible furnace, heated to 900 °C to remelt. Salt flux was added to absorb the contaminants and protect the aluminium metal against oxidation. Refining of the melted aluminium was undertaken to separate the slag from the pure metal. Thereafter, aluminium billets were produced by reheating the pure metal to 900 °C, and subsequently pouring into a preheated mould at 600 °C prepared in a sand core.
2.1.3 Preparation of Aluminium Composites

The modified silver AgNPs was used to prepare 850 g metal matrix composite of aluminium-silver nanoparticles (Al-AgNPs) by melt stirred technique. The aluminium billets were divided into seven portions, measured and labelled as samples 1-6 and C (control sample). Each billet portion was first preheated to 450 °C before finally melted at 750 °C in a crucible furnace. The modified AgNPs of specified percentage weight fraction of 2, 4 and 6% were weighed and preheated at 100 °C and incorporated into the melted aluminium billets, thoroughly mixed at 200 rpm for 10 min and poured into 30 × 200 mm cylindrical mould heated to 600 °C. These procedures were repeated for Al-CaCO₃ only at the same specified percentage weight fraction. Masses of the base metal matrix and percentage weight fractions of the reinforcements are described in Table 3.

| Sample | Percentage fraction of Reinforcement (%) | Mass fraction of Al 6063 (g) | Mass fraction of AgNPs/CaCO₃ (g) | Mass fraction of CaCO₃ (g) | Mass of Composite (g) |
|--------|-----------------------------------------|-----------------------------|---------------------------------|---------------------------|----------------------|
| 1      | 2.00                                    | 833.00                      | 17.00                           | -                         | 850                  |
| 2      | 4.00                                    | 816.00                      | 34.00                           | -                         | 850                  |
| 3      | 6.00                                    | 799.00                      | 51.00                           | -                         | 850                  |
| 4      | 2.00                                    | 833.00                      | -                               | 17.00                     | 850                  |
| 5      | 4.00                                    | 816.00                      | -                               | 34.00                     | 850                  |
| 6      | 6.00                                    | 799.00                      | -                               | 51.00                     | 850                  |
| 7      | C                                       | 850                         | -                               | -                         | -                    |

One sample each was prepared from the casting samples to analyze the microstructure. The samples were etched using abrasive paper of grade 800 and finally polished to obtain a reflective surface finish. The microstructure of each sample was observed by optical microscope. Figure 4(a) reveals micrograph for the grain structure of Al6063 Matrix. Figure 4(b) shows the micrograph of Al-AgNPs. The silver nanoparticles were spread within the interior of the grain also along the grain boundaries of the Al6063 alloy. Figure 4(c) shows the
micrograph of Al-CaCO$_3$. In Figures 4(b) and (c), there was even distribution of AgNPs and CaCO$_3$ particles within the Al6063 alloy.

![Micrograph of Al-CaCO$_3$.](image)

**Figure 4.** (a) Matrix grain structure of Al6063 (b) Micrograph of 2 % Al-AgNPs (c) 2 % Al-CaCO$_3$

### 2.2 Mechanical Properties of the Samples

The samples were machined after solidified, to sizes accordingly to the required mechanical and microstructural analysis to be carried out in accordance with ASTM E23 and E384 Standards.

#### 2.2.1 Impact Analysis

The impact analysis was carried out using Charpy Impact Tester to determine the behaviour of the samples under sudden load which gives the impact strength or energy require to cause deformation or break of the sample. Seven samples from all the combinations of the percentage weight fractions of the composites and control were machined to 55 × 10 × 5 mm charpy specimens with centre V-notch according to ASTM E23. The specimen was placed on the impact tester’s vice such that the notch faces away from the hammer. The scale pointer was set to zero position and safety considerations were considered. The pendulum was released by the release mechanism and the impact energy (E) was recorded directly from the scale. The exercise was repeated twice for each sample and impact strength (IS) was determine by finding the average of the impact energies.
2.2.2 Hardness Analysis

The hardness analysis was carried out using brinell hardness testing machine with 1.5 mm diameter ball and 100 kg load. This is to measure the extent of a localized penetration by a standardized round or pointed indenter in accordance with ASTM E384 standard. The specimens were placed one after the other on the hardness testing table and elevated gradually for the specimen to make contact with the indenter. When secured contact was established, the load lever was moved from point A to B to load the machine, left for 10 seconds. The diameter of the indentation was measured using microscope and micrometer. The expression for the Brinell hardness number is given in equation 1

\[ BHN = \frac{2P}{\pi D(D^2 - d^2)} \]  

(1)

Where D is the diameter of the indenter, d is the indent diameter and P is the load applied.

3. Results and Discussion

The results of the influence of AgNPs impregnated with calcium carbonate on mechanical properties of AA6063 alloy are discussed in this section. These were compared with influence of only calcium carbonate on AA6063.

3.1 Impact Test

Figure 5 shows the variation of energy absorbed by Al6063 alloy with increase in the percentage weight fractions (2, 4 and 6 %) of AgNPs-(CaCO3) and CaCO3 respectively. It was observed that there is increase in impact energy absorbed as the percentage weight fractions of reinforcements increase. Significant increase was observed in the impact strength of AgNPs-(CaCO3)-Al6063 composite compared to CaCO3-Al6063 composite. The addition of reinforcements increases the ductility and deformation capabilities of Al6063 composites [19, 20]. The reinforcement promotes the dislocating motion which is required for plastic deformation of the Al6063 matrix [20]. Impact properties of the composites are also explained as a function of force of cohesion between the metal matrix and the reinforcements [21]. This is obvious in AgNPs-(CaCO3)-Al6063 compared to CaCO3-Al6063 due to the sizes of the AgNPs to CaCO3. Figures 6(a-c) show the SEM images of the fracture surfaces to explain impact energy behaviour of the as-cast Al6063, AgNPs-(CaCO3)-Al6063 and CaCO3-Al6063 composites respectively. The as-cast Al6063 matrix has very less capacity to reduce the dislocating motion required for plastic
deformation, while there are ductile modes fractures in AgNPs-(CaCO₃) and CaCO₃-Al6063 fractograph counterparts [3].

![Figure 5](image-url)  
**Figure 5.** The response of composites to impact energy

![Figure 6](image-url)  
**Figure 6.** (a) SEM fractograph of As-cast Al6063 (b) 2%AgNPs-(CaCO₃)-Al6063 (c) 2% CaCO₃-Al6063

### 3.2 Hardness Test

Hardness testing using the normal Brinell hardness measurement was conducted to determine the level of brittleness of AgNPs-(CaCO₃) and CaCO₃-Al6063 composites as compared to as-cast Al6063 alloy. Figure 7 shows the variation of Brinell hardness numbers the composites with increase in percentage weight fractions of the reinforcements. From the Figure 7, there is continuous increase in the hardness number as the percentage weight fractions of the reinforcements increased. The increase is due to substantial homogeneous dispersion of the reinforcements in the aluminium matrix [17] and therefore acts as problems to the motion of dislocation [22]. Hardness of the composites is a function of the reinforcement and matrix [20].
The presence of silicon in excess as part of the composition of aluminium matrix increases the brittleness and hardness of Al6063 composites [20]. Also, as observed in Figure 7, there is conspicuous margin of increase in hardness between AgNPs-(CaCO₃)-Al6063 and CaCO₃-Al6063 composites. This increase is linked to increase in the percentage weight fraction of hard and brittle phases of the AgNPs-(CaCO₃) particles in Al6063 alloy [23]. The presence of CaCO₃ mixed with AgNPs in the Al6063 alloy raises the dislocation density at the particle-matrix interface due to differences in the thermal expansion coefficient between AgNPs reinforcement and Al metal matrix causing plastic incohesion between the matrix and reinforcement [24-27].

Figure 7. The effect of percentage weight fraction of the composites on hardness

4. Conclusion
Al6063 composites were successfully fabricated via stir casting process using silver nanoparticles synthesized from cob web and calcium carbonate. The effects of silver nanoparticles impregnated with calcium carbonate on mechanical properties of Al6063 alloy were examined. Impact energies and hardness of the composites increase with increase in percentage weight fraction of the reinforcement. Evidence of dimples surfaces was observed in AgNPs-(CaCO₃)-Al6063 and micro-void formation was observed in CaCO₃-Al6063 composite. Application of the AgNPs-(CaCO₃)-Al6063 composite in window frame will be very good in terms of impact and hardness properties especially when strength to weight ratio is a deciding factor.
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