MECHANICAL BEHAVIOUR OF ALUMINA REINFORCED AA 6063 METAL MATRIX COMPOSITES DEVELOPED BY TWO STEP - STIR CASTING PROCESS

ABSTRACT: Among metallic matrices, Aluminum based matrix remains the most explored metal matrix material for the development of MMCs. This is primarily due to the broad spectrum of properties offered by aluminum based matrix composites at low processing cost. The mechanical behavior of aluminum alloy (6063) - alumina particulate composites developed using two step stir casting was investigated. AA 6063 - Al₂O₃ particulate composites having 6, 9, 15, and 18 volume percent of Al₂O₃ were produced. It is observed that AA 6063/Al₂O₃ composites having low porosity levels (≤ 3.51 %porosity) and a good uniform distribution of the alumina particulates in the matrix of the AA 6063 were produced. The tensile strength, yield strength, and hardness increased with increase in alumina volume percent while the strain to fracture and fracture toughness decreased with increasing volume percent alumina.

KEYWORDS: stir casting; AA6063-Al₂O₃, fracture toughness, tensile properties, porosity

INTRODUCTION
The viability of developing simple, cost effective and technically efficient processing routes for the production of metal matrix composites (MMCs) is currently being explored by materials researchers from most developing countries [1 - 2]. The motivation for research in MMCs development is its attractive properties and higher performance potentials over traditional metals and alloys [3 - 4]. Some of the desirable properties of MMCs include high specific strength and stiffness, better high temperature performance, and low thermal expansion [5-6]. Among metallic matrices, Aluminum based matrix remains the most explored metal matrix material for the development of MMCs. This is primarily due to the broad spectrum of properties offered by the aluminum based matrix composites at low processing cost [6]. Currently, Aluminum based matrix composites are applied in the design of a wide range of components for use in aerospace technology, defense, electronic heat sinks, solar panel substrates, antenna reflectors, automotive drive shaft fins, explosion engine components, and sports equipment among others [6 - 7].

Deriving optimized properties from any selected Al based matrix composite requires a sound knowledge of the material behavior of the composite which is influenced by such factors as the base Al alloy composition, the manufacturing process, the reactivity between the reinforcement and the matrix, the size, morphology and volume fraction of the reinforcement [8 - 10].

The current research work is an effort to study the mechanical behaviour of AA (6063)/ Al₂O₃ composites produced using two step stir casting process. AA 6063 is processed in large quantities at lower costs in many developing countries but its potentials for use as Al alloy matrix for composite development has not been explored as extensively as the other age hardenable Al alloy series such as the AA 6061, AA 7075, and AA 2024 series [8, 11 - 12].

MATERIALS AND METHODS. Materials

The materials utilized in the present study are 100 percent chemically pure alumina (Al₂O₃) particles having a particle size of 28 µm and Aluminum 6063 alloy which served as the matrix. The composition of the Aluminum 6063 alloy is shown in Table 1.

Table 1: Chemical Composition of the Aluminum Alloy 6063 (AA 6063)

<table>
<thead>
<tr>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>0.22</td>
<td>0.02</td>
<td>0.03</td>
<td>0.50</td>
</tr>
<tr>
<td>Zn</td>
<td>Cr</td>
<td>Ti</td>
<td>Al</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
<td>Bal.</td>
<td></td>
</tr>
</tbody>
</table>

Methods

Stir Casting

The quantity of Aluminum (6063) alloy and alumina (Al₂O₃) particles required to produce composites having 6, 9, 15, and 18 volume percent alumina were evaluated using charge calculations. The alumina particles were initially preheated at a temperature of 250°C for 5minutes to help improve wettability with the AA 6063 alloy. The AA 6063 ingots were charged into a gas-fired crucible furnace and heated to a temperature of 750°C ± 30°C (above the liquidus temperature of the alloy) and the liquid alloy was...
then allowed to cool in the furnace to a semi solid state at a temperature of about 600°C. The preheated alumina was added at this temperature and stirring of the slurry was performed manually for 5 minutes. The composite slurry was then superheated to 720°C and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 300 rpm for 10 minutes to help improve the distribution of the alumina particles in the molten AA 6063. An external temperature probe (thermocouple) was utilized to monitor the temperature of the furnace. The molten composite was then cast into prepared sand moulds. Unreinforced AA 6063 were also prepared by casting for control experimentation.

**Hardness Measurement**

The hardness of the composites was evaluated using a Vickers Hardness Tester (LECO AT 700 Microhardness Tester). Prior to testing, the surface of the composite test specimens of sizes 25 × 020 mm were subjected to grinding and polishing operation to obtain a flat and smooth surface finish. A direct load of 50gf (490.3 mN) was then applied on the specimens for 10 seconds and the hardness readings evaluated following standard procedures. Multiple hardness tests were performed on each sample and the average value taken as a measure of the hardness of the specimen.

**Density Measurement**

The density measurements were carried out to determine the porosity levels of the samples. This was achieved by comparing the experimental and theoretical densities of each volume percent Al₂O₃ reinforced composite. The experimental density of the samples was evaluated by weighing the test samples having dimensions of 20 mm diameter and 220 mm length using a high precision electronic weighing balance with a tolerance of 0.1mg. The measured weights in each case was divided by the volume of the respective samples.

The theoretical density of composite was evaluated by using the rule of mixtures given by:

\[
\rho_{6063} = \rho_{AA6063} \times V_{AA6063} + \rho_{Al2O3} \times V_{Al2O3} \tag{2.1}
\]

where, \( \rho_{AA6063} \) = Density of Composite, \( V_{AA6063} \) = Volume fraction of AA 6063, \( \rho_{Al2O3} \) = Density of AA 6063, \( V_{Al2O3} \) = Volume fraction AldO₃, and \( \rho_{Al2O3} \) = Density of Al₂O₃.

The percent porosity of the composites was evaluated using the relations [12]:

\[
{\text{porosity}} = \left( \frac{\rho_{T} - \rho_{EX}}{\rho_{T}} \right) \times 100\% \tag{2.2}
\]

where, \( \rho_{T} \) = Theoretical Density (g/cm³), \( \rho_{EX} \) = Experimental Density (g/cm³)

**Tensile Testing**

Room temperature uniaxial tension tests were performed on round tensile samples machined from the monolithic alloy and the composites with dimensions of 6 mm diameter and 30 mm gauge length. The testing was performed using an instron universal testing machine operated at a constant cross head speed of 1mm/s; and the procedure adopted was in conformity with ASTM E8M - 91 standards [13]. Three repeat tests were performed for each test condition to guarantee reliability of the data generated. The tensile properties evaluated from the stress-strain curves developed from the tension test are - the ultimate tensile strength (σₚ), the 0.2% offset yield strength (σ₀.₂), and the strain to fracture (εᵓ).

**Fracture Toughness, K₁C**

Circumferential notch tensile (CNT) specimens were prepared for the evaluation of fracture toughness in accordance with Alaneme [14]. The CNT specimens were machined with gauge length of 30mm, specimen diameter of 6mm (D), notch diameter of 4.5mm (d) and notch angle of 60°. The specimens were then subjected to tensile loading to fracture using an instron universal testing machine. The fracture load \( (P_f) \) obtained from the CNT specimens’ load - extension plots were used to evaluate the fracture toughness using the empirical relations by Dieter [15]:

\[
K_{1C} = \frac{P_f}{(D)^{1/2}} \left[ 1.72(D/d)^{1/2} - 1.27 \right] \tag{2.3}
\]

Where, D and d are respectively the specimen diameter and the diameter of the notched section. The validity of the fracture toughness values was evaluated using the relations in accordance with Nath and Das [16]:

\[
D \geq (K_{1C}/\sigma_{Y})^2 \tag{2.4}
\]

A minimum of two repeat tests were performed for each treatment condition and the results obtained were taken to be highly consistent if the difference between measured values for a given treatment condition is not more than 2%.

**Microstructure**

The microstructural investigation was performed using a Datteng Software-Driven Metallurgical Microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500μm - 1500μm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10μm - 0.5μm with ethanol solvent. The specimens were then etched using 1HNO₃: 1HCl solution by swabbing in accordance with Yussof et al [17] before microstructural examination was performed using the optical microscope.

**RESULTS AND DISCUSSION. Microstructure**

Figure 1 shows representative optical micrograph for the 9 and15 volume percent Al₂O₃ reinforced AA 6063 composites. It is observed that the Al₂O₃ particulates are visible and a good dispersion of the particulates in the AA 6063 matrix is evident. This is a good indicator of the efficiency of the production technique.
The results of the percent porosity of the composites are presented in Table 2. It is observed that slight porosities exist in the produced composites since the experimental densities are lower than the theoretical densities. It is however encouraging that the percent porosities are between 1.08 – 3.51% which is within the acceptable range of 4% porosity reported in literature as the maximum permissible in cast metal matrix composites [18-19].

<table>
<thead>
<tr>
<th>Materials Samples</th>
<th>Theoretical Density (g/cm³)</th>
<th>Experimental Density (g/cm³)</th>
<th>% Porosity</th>
<th>Hardness (VHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2.70</td>
<td>2.68</td>
<td>0.74</td>
<td>40.3 ± 0.2</td>
</tr>
<tr>
<td>6%</td>
<td>2.76</td>
<td>2.69</td>
<td>2.54</td>
<td>40.5 ± 0.1</td>
</tr>
<tr>
<td>9%</td>
<td>2.79</td>
<td>2.74</td>
<td>1.79</td>
<td>41.4 ± 0.4</td>
</tr>
<tr>
<td>15%</td>
<td>2.85</td>
<td>2.75</td>
<td>3.51</td>
<td>43.6 ± 0.2</td>
</tr>
<tr>
<td>18%</td>
<td>2.87</td>
<td>2.77</td>
<td>3.48</td>
<td>45.1 ± 0.3</td>
</tr>
</tbody>
</table>

The low porosity levels are attributed to the two-step stirring process adopted for producing the composites. The manual mixing operation performed in the semi-solid state helps to break the surface gas layers and to spread the liquid metal onto the surface of the particles. It also reduces the surface tension between the AA 6063 melt and the particles to facilitate easier wetting and mixing of the alumina particulates in the melt.

The mechanical stirring employed at the liquidus state helps in reducing the sedimentation of alumina particles by virtue of their higher density (3.95g/cm³); and also improve the dispersion of the alumina particulates.

### Mechanical Properties

The variation of hardness with volume percent Al₂O₃ is also presented in Table 2. It is observed that the hardness increases with increase in volume percent Al₂O₃. This trend is due to an increase in the proportion of the hard Al₂O₃ particulates in the composites, which increases the composites resistance to indentation in comparison to the monolithic alloy [18].

The stress-strain plots of the composites are presented in Figure 2; while the variation of ultimate tensile and yield strengths and strain to fracture are presented in Figures 3 - 4. It is observed from the stress-strain plots that the monolithic alloy has the largest plastic strain and also exhibits the least resistance to plastic deformation judging from its relatively lower flow stress in comparison with the composites.

![Figure 3](image-url)  
**Figure 3:** Variation of Ultimate Tensile and Yield Strengths in the Composite with increase in Volume percent alumina reinforcement.

Figure 3 shows clearly that the ultimate tensile and yield strengths of the composites increases with increase in volume percent alumina.
The observed trend is in conformity with observations in most hard particulate reinforced metal matrix composites [20-21]. The strengthening mechanisms has been well reported by Chawla and Shen [22] who attributed it to increased load sustaining capacity of the composite with increase in the volume percent of the hard particulates; and the increased resistance to dislocation movement by the particulates. The resulting thermal mismatch between the high expansion metallic matrix and the low expansion ceramic particulates results in the generation of dislocations at the reinforcement/matrix interface upon cooling, contributing to an increase in dislocation density in the composites with increasing particulate content [22 - 23].

The strains to fracture for the composites (Figure 4) are observed to decrease with increase in volume percent alumina; and the values are observed to be less than 0.19 (19%). The increased matrix/particulate interfaces with increase in volume percent alumina leads to an increase in the potential sites for void nucleation or micro-crack formation. The uneven plastic strain at the interface facilitates the nucleation of voids or micro-cracks [22-24].

The fracture loads utilized for the evaluation of the fracture toughness were derived from the stress-strain plots of the circumferential notch tensile specimens (Figure 5).

The variation of fracture toughness of the composites with increase in Al₂O₃ volume percent is presented in Figure 6. The results were taken to be reliable because the requirement for nominal plain strain condition was met with the specimen diameter of 6mm since the relation \( D \geq (K_{IC}/\sigma_y)^{2/3} \) [16] was utilized to test for the validity of the \( K_{IC} \) values evaluated from the CNT testing. The fracture toughness (which is a measure of the composites resistance to crack propagation) was observed to decrease with increase in volume percent of Al₂O₃ which is consistent with the trend in most hard particle reinforced metal matrix composites [22, 25-26]. The increased sites (particles, particle/matrix interfaces, and particle clusters) for crack nucleation with increasing volume percent of the Al₂O₃ were responsible for the observed trend [26 - 27]. The fracture micro-mechanism may be due to particulate cracking, interfacial cracking or particle debonding [27 - 28]. Generally, the fracture toughness values obtained for the composites were found to be comparable to that of Al matrix composites processed under similar conditions [29-30].

CONCLUSIONS

From the results of this research investigation, It has been established that low porosity levels less than 3.6% is observed in AA 6063/Al₂O₃p composites developed by the two step stir casting process adopted in this research. The tensile strength, yield strength, and hardness values of the composites increased with increase in alumina volume percent while the strain to fracture and fracture toughness decreased with increasing volume percent alumina. The mechanical properties obtained from the AA 6063/Al₂O₃p composites developed compares favorably with that of other aluminum based alumina reinforced composites reported in literature.
REFERENCES


