INFLUENCE OF THERMO-MECHANICAL TREATMENT ON THE TENSILE BEHAVIOUR AND CNT EVALUATED FRACTURE TOUGHNESS OF BORAX PREMIXED SiC\textsubscript{p} REINFORCED AA 6063 COMPOSITES

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ABSTRACT

The influence of thermo-mechanical treatment on the percent porosity and mechanical behaviour of SiC reinforced aluminium alloy (6063) composites was investigated. AA 6063 – SiC\textsubscript{p} composites having 6 and 9 vol. % of SiC were produced by the use of Borax additive and double stir casting process. The composites were cold rolled to 20, 25 and 35% deformation before solution heat-treating at 550°C for 1 hour cooling rapidly in water. Density measurements and percent porosity of the composites were evaluated; also their tensile properties and fracture toughness were assessed. The results indicate that the cold rolling and solution heat-treating processes resulted in remarkable reduction in porosity levels in the composites (≤1.9 % porosity). A good uniform distribution of the SiC particulates in the AA 6063 was also produced. The tensile properties and fracture toughness of the composites improved significantly with the adoption of the cold rolling and solution heat-treatment process.

Keywords: Stir casting, AA 6063 – SiC\textsubscript{p}, Thermo-mechanical heat-treatment, Mechanical behaviour, Density measurement

1. INTRODUCTION

The improved service performance of metal matrix composites (MMCs) over most conventional monolithic materials in engineering applications is linked to its unique combination of properties (Alaneme, 2011a; Miracle, 2005). Some of the remarkable property combinations of MMCs are high specific strength and stiffness, better high temperature strength and stability in comparison to its base alloy, high thermal conductivity and low thermal coefficient of expansion, improved tribological properties and satisfactory levels of corrosion resistance (Anilkumar et al., 2011; Alaneme, 2011b; Oguocha, 1999; Zamri et al., 2011). Among MMCs, Aluminium based metal matrix composites (AMCs) have been the most developed and utilized for a wide range of engineering applications (Surappa, 2003). The most pronounced areas of application of AMCs are in automobile, railway, and aerospace transport technologies where they are utilized for the design of components such as: engine cylinder blocks and pistons, brake discs and drums, automobile drive shafts, brake discs for railway applications, fan exit guide vanes, and blade sleeves for aerospace applications (Chawla et al., 2009; Adiamak, 2006).

There have been sustained efforts by materials researchers to develop AMCs using simple, cost-effective, and technically efficient processing techniques. Two step stir casting has been explored to develop AMCs with very encouraging results with regards lowered porosity levels (less than 4 %) achieved (Zhou and Xu, 1997). However, in the as-cast or solution heat-treated conditions some of the AMCs do not possess optimized toughness and mechanical strength even when porosity levels appear to be satisfactory (Alaneme and Aluko, 2012a). Recently, there has been interest to develop AMCs based on the use of Aluminium alloy 6063 (Alaneme and Aluko, 2012a; Alaneme and Aluko, 2012b; Khalifa and Mahmoud, 2009). This research work is aimed at improving the mechanical properties of AA 6063 – SiC particulate composites by adopting cold rolling and solution heat-treatment in combination as a secondary processing treatment for the production of the AMCs.

2. MATERIALS AND METHODS

2.1 Materials

100 percent chemically pure silicon carbide (SiC) particles having particle size of 30\textmu m and Aluminium alloy 6063 (AA 6063) which served as the matrix; were utilized for the production of the composite. Hydrated sodium tetra borate (borax) (Na\textsubscript{4}B\textsubscript{4}O\textsubscript{7}.10H\textsubscript{2}O was used for improvement of wettability of the molten aluminum alloy 6063 and the silicon carbide particles during melting. The composition of the Aluminium alloy 6063 is shown in Table 1.

| Table 1 Chemical Composition of the Aluminium Alloy 6063 (AA 6063) |
|-------------------|---|---|---|---|---|---|---|---|---|
| Si        | Fe | Cu | Mn | Mg | Zn | Cr | Ti | Al |
| .45      | .22 | .02 | .03 | .50 | .02 | .03 | .02 | Bal. |

2.2 Method

2.2.1 Stir Casting

The quantities of Aluminium (6063) alloy and silicon carbide (SiC) particles required to produce composites having 6 and 9 volume percent silicon carbide were determined by charge calculations. The silicon carbide was premixed with dehydrated Borax in ratio 1:2 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 5-10 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 300rpm for 10minutes to help improve the distribution of the alumina particles in the molten AA 6063. The molten composite was then cast into prepared sand moulds. Unreinforced AA 6063 were also prepared by casting for control experimentation.

2.2.2 Cold Rolling and Solution Heat-treatment Processing

The cast composites of 6 and 9 volume percent silicon carbide along with the unreinforced alloy; were subjected to cold deformation using a miniature cold rolling machine. The composites were rolled to 20, 25 and 35 % degrees of deformation using the round orifice of the cold rolling machine before solution heat-treating the samples at 550°C for 1 hour cooling rapidly in water. The sample designations for the different temper conditions (as-cast, 20%, 25% and 35% cold rolled and solution heat-treated conditions) are presented in Table 2.

2.2.3 Density Measurement

Density measurements were carried out to determine the porosity levels of the composites produced. This was achieved by comparing the experimental and theoretical densities of each volume percent SiC reinforced composite (both for the as-cast and the cold rolled – solution heat-treated conditions). The experimental density of the samples was evaluated by weighing the test samples using a high precision electronic weighing balance with a tolerance of 0.1mg. The measured weights in each case were divided by the volume of the respective samples. The theoretical density was evaluated by using the rule of mixtures given by:

\[ \rho_{AA\ 6063SiC_p} = Vol.\ AA\ 6063 \times \rho_{AA\ 6063} + Vol.\ SiC \times \rho_{SiC} \]  

(1)

where, \( \rho_{AA\ 6063SiC_p} \) = Density of Composite, \( Vol.\ AA\ 6063 \) = Volume fraction of AA 6063, \( \rho_{AA\ 6063} \) = Density of AA 6063, \( Vol.\ SiC \) = Volume fraction SiC, and \( \rho_{SiC} \) = Density of SiC.

The percent porosity of the composites was evaluated using the relations:

\[ \%\ porosity = \{(\rho_T - \rho_{EX}) \div \rho_T\} \times 100\% \]  

(2)

Where, \( \rho_T \) = Theoretical Density (g/cm³), \( \rho_{EX} \) = Experimental Density (g/cm³)

Table 2 Sample Designation for the Different Temper Conditions

<table>
<thead>
<tr>
<th>Temper Condition</th>
<th>Volume Percent</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-cast</td>
<td>A1</td>
<td>0</td>
</tr>
<tr>
<td>20% Cold-rolled +</td>
<td>A2</td>
<td>6</td>
</tr>
<tr>
<td>solution heat-treated</td>
<td>B1</td>
<td>9</td>
</tr>
<tr>
<td>25% Cold-rolled +</td>
<td>A3</td>
<td>6</td>
</tr>
<tr>
<td>solution heat-treated</td>
<td>B2</td>
<td>9</td>
</tr>
<tr>
<td>35% Cold-rolled +</td>
<td>A4</td>
<td>6</td>
</tr>
<tr>
<td>solution heat-treated</td>
<td>B4</td>
<td>9</td>
</tr>
</tbody>
</table>

2.2.4 Tensile Testing

Room temperature uniaxial tension tests were performed on round tensile samples machined from the unreinforced aluminium alloy and the processed AA 6063 – SiCp 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 standards (1991). 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 (\( \sigma_u \)), the 0.2% offset yield strength (\( \sigma_y \)), and the strain to fracture (\( \varepsilon_f \)).

Circumferential notch tensile (CNT) specimens were also prepared for the evaluation of fracture toughness the composites in accordance with Alaneme (2011c). 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 relation by Dieter (1988):

\[ K_{IC} = P_f / (D)^{3/2} [1.72(D/d) - 1.27] \]

(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 in accordance with Alaneme (2011c). A minimum of two repeat tests were performed for each treatment condition to ensure the reliability of the results generated.

2.2.5 Microstructure

The microstructures of the composites were examined using a Zeiss Metallographic Microscope. The test specimens were prepared for the examination following standard metallographic practice reported in details by Alaneme and Aluko (2012b). The specimens were etched using 1HNO₃: 1HCl solution by swabbing before microstructural examination was performed.
3. RESULTS AND DISCUSSION

3.1 Composite Density and Percent Porosity

Table 3 Comparison of Percentage Porosity of the AA6063-SiC\textsubscript{p} Composites

<table>
<thead>
<tr>
<th>Sample Designation</th>
<th>Theoretical density</th>
<th>Experimental density</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>2.70</td>
<td>2.66</td>
<td>1.48</td>
</tr>
<tr>
<td>A2</td>
<td>2.70</td>
<td>2.67</td>
<td>1.11</td>
</tr>
<tr>
<td>A3</td>
<td>2.70</td>
<td>2.675</td>
<td>0.93</td>
</tr>
<tr>
<td>A4</td>
<td>2.70</td>
<td>2.68</td>
<td>0.74</td>
</tr>
<tr>
<td>B1</td>
<td>2.72</td>
<td>2.675</td>
<td>1.65</td>
</tr>
<tr>
<td>B2</td>
<td>2.72</td>
<td>2.685</td>
<td>1.28</td>
</tr>
<tr>
<td>B3</td>
<td>2.72</td>
<td>2.69</td>
<td>1.10</td>
</tr>
<tr>
<td>B4</td>
<td>2.72</td>
<td>2.695</td>
<td>0.92</td>
</tr>
<tr>
<td>C1</td>
<td>2.736</td>
<td>2.684</td>
<td>1.9</td>
</tr>
<tr>
<td>C2</td>
<td>2.736</td>
<td>2.69</td>
<td>1.68</td>
</tr>
<tr>
<td>C3</td>
<td>2.736</td>
<td>2.70</td>
<td>1.31</td>
</tr>
<tr>
<td>C4</td>
<td>2.736</td>
<td>2.705</td>
<td>1.13</td>
</tr>
</tbody>
</table>

The results of the density measurements and percent porosity of the as-cast, 20, 25 and 35\% cold rolled and solution heat-treated AA 6063/SiC\textsubscript{p} composites are presented in Table 3. It is observed that for all volume percent of the AA 6063-SiC composites, the as-cast temper had the highest porosity levels in comparison with the cold rolled and solution heat-treated tempers. It is noted that the percent porosity of the composites increases with increase in volume percent SiC and decreases with the degree of cold rolling. This is an indication that the cold rolling and solution heat-treating process helps in improving the quality of the cast composites by reducing the percent porosity. The process also results in improved dispersion of the SiC particulates in the AA 6063 matrix in comparison with the as-cast structures as revealed by the representative optical micrographs presented in Figure 1. Figure 1(a) which is an optical micrograph for the as-cast AA 6063-6 vol. \% SiC\textsubscript{p} composite shows that the SiC particles are not evenly distributed in the AA 6063 matrix. Also, slight particle agglomeration is still observed in the as-cast structure. This is in contrast with Figure 1(b) (the optical micrograph of AA 6063-6 vol. \% SiC\textsubscript{p} composite subjected to 35\% cold rolling and solution heat-treatment) where a more even dispersion of the SiC particles in the AA 6063 matrix is observed.

3.2 Mechanical Properties

Figure 2 Variation of Ultimate Tensile Strength and Yield Strength for the AA 6063 – SiC\textsubscript{p} Composites Produced

The variation of ultimate tensile and yield strengths, strain to fracture, and fracture toughness of the composites are presented in Figures 2 - 4. Figure 2 shows as expected that the ultimate tensile and yield strengths of the composites increases with increase in volume percent SiC, but noteworthy is the fact that the strength of the composites improves significantly with the cold rolling and solution heat-treatment process. The cold rolling and solution heat-treatment helps in achieving a refined and homogeneous structure by removing voids and micro-voids and also helps in redistributing the particulates and second phase particles resulting in considerable elimination of particle clusters and segregation (Courtney, 2006; Huda, 2009; Shahani and Clyne, 2003). The elimination of a considerable amount of voids and porosity in the composite helps in reducing the tendency of particle pullout during tensile loading.
thereby enhancing the strengthening capacity of the composites (Chawla and Shen, 2001).

The strains to fracture for the composites (Figure 3) are observed to decrease with increase in volume percent alumina but improve slightly with the cold rolling and solution heat-treatment process. The reduced porosity of the cold rolled and solution heat-treated composites is largely responsible for the improved strain to fracture of the composites, as there is reduced tendency for micro-crack coalescence and particle pullout during tensile loading (Pakdel et al., 2007).

Figure 3 Variation of Strain to Fracture for the AA 6063 – SiC<sub>p</sub> Composites Produced

The strains to fracture for the composites (Figure 3) are observed to decrease with increase in volume percent alumina but improve slightly with the cold rolling and solution heat-treatment process. The reduced porosity of the cold rolled and solution heat-treated composites is largely responsible for the improved strain to fracture of the composites, as there is reduced tendency for micro-crack coalescence and particle pullout during tensile loading (Pakdel et al., 2007).

Figure 4 Variation of Fracture Toughness for the AA 6063 – SiC<sub>p</sub> Composites Produced

The variation of fracture toughness of the composites with increase in SiC volume percent is presented in Figure 4. The results were taken to be reliable because the requirement for nominal plain strain condition was met with the specimen diameter of 6mm when the relation D ≥ (K<sub>IC</sub>/σ<sub>y</sub>)<sup>2</sup> by Nath and Das (2006) was utilized to test for the validity of the K<sub>IC</sub> values determined from the CNT testing. The fracture toughness was observed to decrease with increase in volume percent of SiC but improves with degree of cold rolling before solution heat-treatment. The fracture micromechanism in particulate reinforced MMCs have been reported to be due to particulate cracking, interfacial cracking or particle debonding (Ranjbaran, 2010; Milan and Bowen, 2004). The reduced porosity and considerable elimination of particle clusters in the composites is responsible for the slight improvement in the fracture toughness of the composites.

4. CONCLUSION
The results indicate that the cold rolling and solution heat-treatment processes resulted in remarkable reduction in porosity levels in the AA 6063/ SiC<sub>p</sub> composites (≤ 1.9 % porosity). A good uniform distribution of the silicon carbide particulates in the matrix of the AA 6063 was also produced. The tensile properties and fracture toughness of the composites improved significantly with the adoption of the cold rolling and solution heat-treatment process.

REFERENCES
Alaneme, K.K. and Aluko, A.O. (2012a). Fracture Toughness (K<sub>IC</sub>) and Tensile Properties of As-Cast and Age-Hardened Aluminium (6063) – Silicon Carbide Particulate Composites, Scientia Iranica (Elsevier), Iran (In press).