PREPARATION OF 6061Al-Al$_2$O$_3$ METAL MATRIX COMPOSITE BY STIR CASTING AND EVALUATION OF MECHANICAL PROPERTIES

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ABSTRACT

Aluminum MMCs are preferred to other conventional materials in the fields of aerospace, automotive and marine applications owing to their improved properties like high strength to weight ratio, good wear resistance etc. In the present work an attempt has been made to synthesize metal matrix composite using 6061Al as matrix material reinforced with ceramic Al$_2$O$_3$ particulates using liquid metallurgy route in particular stir casting technique. The addition level of reinforcement is being varied from 6 - 12wt% in steps of 3wt%. For each composite, reinforcement particles were preheated to a temperature of 200$^\circ$C and then dispersed in steps of three into the vortex of molten Al6061 alloy to improve wettability and distribution. Microstructural characterization was carried out for the above prepared composites by taking specimens from central portion of the casting to ensure homogeneous distribution of particles. Hardness and tensile properties of the prepared composite were determined before and after addition of Al$_2$O$_3$ particulates to note the extent of improvement. Microstructural characterization of the composites has revealed fairly uniform distribution and some amount of grain refinement in the specimens. Further, the hardness and tensile properties are higher in case of composites when compared to unreinforced 6061Al matrix, also increasing addition level of reinforcement has resulted in further increase in both hardness and tensile strength.

KEY WORDS: MMC’s, Al$_2$O$_3$ Particulates, 6061Al, Stir-Casting

INTRODUCTION

Metal–matrix composites (MMCs) are most promising materials in achieving enhanced mechanical properties such as: hardness, Young’s modulus, yield strength and ultimate tensile strength due to the presence of micro-sized reinforcement particles into the matrix. [1, 2]. Aluminum-matrix composites
(AMCs) reinforced with discontinuous reinforcements are finding increased use in automotive, military, aerospace and electricity industries because of their improved physical and mechanical properties [3]. Among Al-alloys, 6061Al-alloy is widely used in engineering applications such as transport and construction sectors where superior mechanical properties like tensile strength, hardness etc., are essentially required [1, 4]. A number of materials such as SiC, Al₂O₃, B₄C, TiB₂, ZrO₂, SiO₂ and graphite are being used as reinforcements to improve the properties of 6061Al alloy. However, the applications of Al₂O₃ or SiC particle reinforced aluminum alloy matrix composites in the automotive and aircraft industries is gradually increasing for pistons, cylinder heads, connecting rods etc. where the tribological properties of the materials are very important [1–5].

The mechanical properties of MMCs are very sensitive to the method of processing being used. Considerable improvements may be achieved by applying science-based modeling techniques to optimize the processing procedure. Several techniques have been employed to prepare the composites including powder metallurgy, melt techniques and squeeze casting [2-3, 6]. However, powder metallurgy appears to be the preferred process in view of its ability to give more uniform dispersions. Hot extrusion is generally used as post-treatment to take the advantages of applying compressive forces and high temperatures, simultaneously [7].

Although powder metallurgy produces better mechanical properties in MMCs, liquid state processing has some important advantages. They are as: better matrix-particle bonding, easier control of matrix structure, simplicity, low cost of processing, nearer net shape and the wide selection of materials [1–4]. Liquid state fabrication of MMC’s includes two methods which depend on the temperature at which the particles are introduced into the melt. In melt stirring process, the particles are incorporated above the liquidus temperature of the molten alloy, while in compo-casting method the particles are incorporated at the semi-solid slurry temperature of the alloy. In both processes, the vortex is used for introducing reinforcement particles. However, the melting process has two major problems firstly, the ceramic particles are generally not wetted by the liquid metal matrix, and secondly, the particles tend to sink or float according to their density relative to the liquid metal. Wettability can be defined as the ability of a liquid to spread on a solid surface and it represents the extent of intimate contact between liquid and solid [8]. Consequently, it results in poor dispersion of the ceramic particles, high porosity and low mechanical properties of the composite. This represents a great challenge of synthesizing cast MMC’s. Poor wettability means the molten matrix cannot wet the surface of reinforcement particles as a result they simply float on the surface owing to surface tension, large surface area, high interfacial energy and presence of oxide film on the melt surface. Improvement in wettability to certain extent can be achieved by several methods like mechanical stirring, preheating the particles to remove adsorbed gases from particle surface [9], addition of alloying elements, use of surface coatings on reinforcement particle etc [10]. Another problem is distribution of reinforcement particles in molten matrix. Due to density difference between matrix and reinforcement, these particles tend
to float or settle in the molten matrix as a result of agglomeration and clustering of the particles will occur [9]. It has been reported that injection of particles with inert carrier gas is helpful in improving the distribution [9]. Therefore, it is essential to develop a method for producing Al-MMC’s taking account of incorporation and distribution reinforcing particles in the molten matrix.

The aim of present study is to synthesize 6061Al-Al$_2$O$_3$ particulate MMC by stir casting method. In order to improve wettability and distribution of reinforcing particles a novel three stage mixing combined with preheating of the reinforcing particles is being adopted.

**EXPERIMENTAL DETAILS**

The matrix material used for the present study is 6061Al-alloy. The chemical composition of matrix material is as shown in Table 1 determined using Atomic Absorption Spectrophotometer (model AA-670, Varian, The Netherlands). Al$_2$O$_3$ particles with size of 125µm and with varying amounts of 6, 9 and 12wt% are being used as reinforcing material in the preparation of composites. Stir casting technique has been used for the preparation of composites. Initially calculated amount of 6061Al alloy was charged into SiC crucible and superheated to a temperature of 800°C in an electrical resistance furnace. The furnace temperature was controlled to an accuracy of ±50°C using a digital temperature controller. A novel three stage mixing combined with preheating of the reinforcing particles is followed. Ceramic Al$_2$O$_3$ particulates were preheated to a temperature of 200°C in an oven to remove the adsorbed gases from the particle surface and to avoid high drop of temperature after addition of particulates. Preheated Al$_2$O$_3$ particles were introduced into the vortex of the molten alloy after effective degassing using solid hexachloroethane (C$_2$Cl$_6$). Vortex is generated with the help of a zirconia coated steel impeller. The extent of incorporation of Al$_2$O$_3$ particles in the matrix alloy was achieved in steps of 3. i.e. Total amount of reinforcement required was calculated and is being introduced into the melt 3 times rather than introducing all at once. At every stage before and after introduction of reinforcement, mechanical stirring is carried out for a period of 10 min. The stirrer was preheated before immersing into the melt, and is located approximately to a depth of 2/3 height of the molten metal from the bottom and run at a speed of 200 rpm. Composite mixture was poured into permanent cast iron moulds having diameter 12.5mm and length of 125mm at a pouring temperature of 750°C.

The prepared composites were characterized by microscopic studies. Specimens of 12mm diameter and thickness of 10mm were cut from the central portion of the casting for microstructural studies conducted using Optical microscopy(model DS X100,Olympus). The density of the samples were measured by Archimedes’s method while theoretical density is computed by taking densities of 6061Al matrix and Al$_2$O$_3$ particles as 2.7 and 3.9gm/cm$^3$ respectively. To investigate the mechanical behavior of the composites the hardness and tensile tests were carried out using Zwick and computerized uni-axial tensile testing machine.
Fig. 1. Shows the dimensions of the mould and specimen used for tensile studies. The Micro-Vickers hardness values of the composites before and after addition of Al\textsubscript{2}O\textsubscript{3} particles were measured with a load of 20N using MVH-II digital micro hardness tester (Zwick/Roell indentec). The hardness value reported is the average value of 100 readings taken at various locations on the polished specimen. Similarly tensile tests were carried out before and after addition of Al\textsubscript{2}O\textsubscript{3} particles and for each of the composite three tests were conducted and average value is reported.

Table 1 Shows the Chemical Composition of Al6061 alloy assessed using Atomic Absorption Spectrophotometer (Model AA-670, Varian, The Netherlands)

<table>
<thead>
<tr>
<th>Elements</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
<th>Ti</th>
<th>Sn</th>
<th>Mg</th>
<th>Cr</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentages</td>
<td>0.4</td>
<td>0.7</td>
<td>0.24</td>
<td>0.13</td>
<td>0.0</td>
<td>0.24</td>
<td>0.25</td>
<td>0.1</td>
<td>0.0</td>
<td>0.80</td>
<td>2</td>
<td>0.25</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

Microstructural Studies

Fabrication of metal–matrix composites with alumina particles by casting processes is usually difficult because of the very low wettability of alumina particles and agglomeration phenomena which results in non-uniform distribution and poor mechanical properties. In the current work, an attempt has been made to prepare Al6061 aluminum alloy matrix composites with micro size alumina particles by stir casting method with a novel three stages mixing combined with preheating of the reinforcing particles. The magnitude of alumina powder used in the composites was 6, 9 and 12wt. %. The optical micrographs of the 6061Al alloy with 0, 6, 9 and 12wt. % Al\textsubscript{2}O\textsubscript{3} particulates were shown in Fig 3(a-g).

Fig. 3a-g shows microstructure of as cast 6061Al and 6061Al with 6 wt% (Fig. 3b-c), 9wt% (Fig. 3d-e) and 12wt% (Fig. 3f-g) Al\textsubscript{2}O\textsubscript{3} particulates. The microstructure of the prepared composites contains primary $\alpha$-Al dendrites and eutectic silicon, while Al\textsubscript{2}O\textsubscript{3} particles are separated at inter-dendritic regions and
in eutectic silicon. The stirring of melt before and after introducing particles has resulted in breaking of
dendrite shaped structure into equiaxed form, it improves the wettability and incorporation of particles within
the melt and also it causes to disperse the particles more uniformly in the matrix. Fig. 3b-e reveals the
distribution of alumina particles in different specimens and it can be observed that there is fairly uniform
distribution of particles and also agglomeration of particles at few places were observed in the composites
reinforced with 6wt%, 9wt% and12wt% Al₂O₃. The microphotographs also indicate that the Al₂O₃ particles
have tendency to segregate and cluster at inter-dendritic regions which are surrounded by eutectic silicon
(Fig. 3b–g). Further, the micrographs show that grain size of the reinforced composite (Fig.3.a-g) is smaller
than the alloy without alumina particles (Fig. 3a) because, Al₂O₃ particles added to melt also act as
heterogeneous nucleating sites during solidification.

Density Measurements

Table 3.1 is presented with the comparison of theoretical density obtained by rule of mixture and measured
density values by experiment for both the composites studied for different wt% of reinforcements.
Experimentally, the density of a composite is obtained by displacement techniques [11] using a physical
balance with density measuring kit as per ASTM: D 792-66 test method. Further, the density can also be
calculated from porosity and apparent density values (sample mass and dimensions) [12].

From the table 3.1 it can be concluded that the experimental density of composite containing 6, 9 and 12 wt%
Al₂O₃p is less when compared to the theoretical density. Further, measured density of composites is lesser
than theoretical density, could be due to the presence of porosity. The porosity is probably due to i) increase
in surface area in contact with air (ii) gas entrapment during stirring; (iii) gas injection of particles introduces
a quantity of gas into the melt; (iv) hydrogen evolution; (v) the pouring distance from the crucible to the
mold and (vi) shrinkage during solidification [13].

Table 3.1: showing the theoretical and measured densities of as cast 6061Al and with 6 wt% of Al₂O₃p
respectively

<table>
<thead>
<tr>
<th>Composition</th>
<th>Theoretical Density (g/cm³)</th>
<th>Measured Density(g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061Al+6% Al₂O₃p</td>
<td>2.74</td>
<td>2.57</td>
</tr>
<tr>
<td>6061Al+9% Al₂O₃p</td>
<td>2.76</td>
<td>2.58</td>
</tr>
<tr>
<td>6061Al+12% Al₂O₃p</td>
<td>2.79</td>
<td>2.35</td>
</tr>
</tbody>
</table>
Hardness Measurements

Fig. 3.2 shows the results of micro hardness tests conducted on Al6061 alloy and the 6061Al composite containing different weight percentage of Al₂O₃ particles. The Micro-Vickers hardness were measured on the polished samples using diamond cone indentor with a load of 20N and the value reported is average of 100 readings taken at different locations. A significant increase in hardness of the alloy matrix can be seen with addition of Al₂O₃ particles. Higher value of hardness is clear indication of the fact that the presences of particulates in the matrix have improved the overall hardness of the composites. This is true due to the fact that aluminum is a soft material and the reinforced particle especially ceramics material being hard, contributes positively to the hardness of the composites. The presence of stiffer and harder Al₂O₃ reinforcement leads to the increase in constraint to plastic deformation of the matrix during the hardness test. Thus increase of hardness of composites could be attributed to the relatively high hardness of Al₂O₃ itself.

![Graph showing the variations in hardness of 6061Al before and after addition of different wt% of Al₂O₃ particulates](image)

Tensile Properties

To investigate the mechanical behavior of the composites the tensile tests were carried out using computerized uni-axial tensile testing machine as per ASTM standards. Three specimens were used for each test and average value is reported. The tensile properties, such as, tensile strength, yield strength and %
elongation were extracted from the stress-strain curves and are represented in Table 3.2. and Fig. 3.3a-b. From fig. it is clear that fracture strength of composites (6, 9 and 12 wt %) is higher when compared to as cast 6061Al, while ductility of composite is lesser that unreinforced alloy. It is also clear from fig. that the tensile strength increases with increase in amount of reinforcement, while there is decrease in ductility with increasing amount of reinforcement. Increase in strength is possibly due to the thermal mismatch between the metallic matrix and the reinforcement, which is a major mechanism for increasing the dislocation density of the matrix and therefore, increasing the composite strength. However, the composite materials exhibited lower elongation than that of unreinforced specimens. It is obvious that plastic deformation of the mixed soft metal matrix and the non-deformable reinforcement is more difficult than the base metal itself. As a result, the ductility of the composite drops down when compared to that of unreinforced material.

**Table 3.2: showing the tensile test results of as cast 6061Al, with addition of 6, 9 and 12 wt% of Al2O3 particulates to 6061Al**

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Weight percentage of Al2O3 particles (%)</th>
<th>Yield Stress (MPa)</th>
<th>Ultimate Tensile strength (MPa)</th>
<th>Extent of Improvement in UTS Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>138.06</td>
<td>149.76</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>145.51</td>
<td>167.93</td>
<td>12.12</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>155.94</td>
<td>173.61</td>
<td>15.92</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>178.91</td>
<td>193.47</td>
<td>29.18</td>
</tr>
</tbody>
</table>

Figure. 3.3 Graphs showing the tensile test results of 6061Al-alloy before and after addition of Al2O3 particulates

(a) Variation in ultimate tensile strength  
(b) Variation in % elongation
CONCLUSIONS

The present work on preparation of 6061Al-Al$_2$O$_3$ metal matrix composite by stir casting and evaluation of mechanical properties has led to following conclusions

1. The composites containing 6061Al with 6, 9 and 12wt% of Al$_2$O$_3$ particulates were successfully synthesized by melt stirring method using three stages mixing combined with preheating of the reinforcing particles.

2. The optical micrographs of composites produced by stir casting method shows fairly uniform distribution of Al$_2$O$_3$ particulates in the 6061Al metal matrix.

3. The microstructure of the composites contained the primary $\alpha$-Al dendrites and eutectic silicon. While Al$_2$O$_3$ particles were separated at inter-dendritic regions and in the eutectic silicon.

4. It was revealed that the hardness of composite increased with increasing the weight percentage of Al$_2$O$_3$ particles.

5. Strength of prepared composites both tensile and yield was higher in case of composites, while ductility of composites was less when compared to as cast 6061Al. Further, with increasing wt% of Al$_2$O$_3$, the tensile strength shows an increasing trend.

REFERENCES


APPENDICES
Preparation of 6061Al-Al₂O₃ Metal Matrix Composite by Stir Casting and Evaluation of Mechanical Properties

Figure 3-(a-g) Showing the optical microphotographs of 6061Al with and without Al₂O₃ particulates (a) As-cast (b) with 6wt% of Al₂O₃p at 50X (c) with 6wt% of Al₂O₃ at 100X (d) with 9wt% of Al₂O₃p at 50X (e) with 9wt% of Al₂O₃p at 100X (f) with 12wt% of Al₂O₃p at 50X (g) with 12wt% of Al₂O₃p at 100X