Physio-mechanical Properties of Aluminium Metal Matrix Composites Reinforced with Al$_2$O$_3$ and SiC

D. Sujan, Z. Oo, M. E. Rahman, M. A. Maleque, C. K. Tan

Abstract—Particulate reinforced metal matrix composites (MMCs) are potential materials for various applications due to their advantageous of physical and mechanical properties. This paper presents a study on the performance of stir cast Al$_2$O$_3$ SiC reinforced metal matrix composite materials. The results indicate that the composite materials exhibit improved physical and mechanical properties, such as, low coefficient of thermal expansion, high ultimate tensile strength, high impact strength, and hardness. It has been found that with the increase of weight percentage of reinforcement particles in the aluminium metal matrix, the new material exhibits lower wear rate against abrasive wearing. Being extremely lighter than the conventional gray cast iron material, the Al-Al$_2$O$_3$ and Al-SiC composites could be potential green materials for applications in the automobile industry, for instance, in making car disc brake rotors.

Keywords—Metal Matrix Composite, Strength to Weight Ratio, Wear Rate

I. INTRODUCTION

PARTICULATE reinforced light metals have shown great promise because of their outstanding mechanical and physical properties. A major goal in manufacturing and utilizing metal matrix composites (MMCs) is to achieve the highest possible strength to weight and weight to stiffness ratios in a low cost light material. Particulate reinforced aluminium matrix composites are widely used in its application in the automotive industries because of their low cost and isotropy in property values [1, 2]. Automotive vehicle braking system is subjected to high wearing. Therefore, brake failure could be minimized by using materials with low wearing rate and high hardness [1-3]. Car manufacturers focus their attention on the design and manufacturing of fuel efficient cars. By having low-density and light-weight brake rotors, fuel consumption of vehicles would be reduced. It has been found that the mechanical properties of aluminium matrix composites are affected by the volume fraction of the reinforcement particles [4].

It is hypothesized that aluminium metal matrix composites with Al$_2$O$_3$ and SiC particle reinforcements could be reliable materials to replace the conventional gray cast iron in the automobile industry. Factors affecting the strengthening properties of the composites would be the amount and dispersion or distribution of the reinforcement particles in the metal matrix.

In this paper, aluminium metal matrix composites with silicon carbide (SiC) and Aluminium oxide (Al$_2$O$_3$) as reinforcement particles are studied to evaluate their physical and mechanical properties. The microstructure of composite material are also discussed in this paper.

II. EXPERIMENTAL PROCEDURE

The composites used in the experiments are produced by the stir casting method [5]. For Al-Al$_2$O$_3$ composite material, Al356 alloy powders are mixed with Aluminium oxide (Al$_2$O$_3$) particles of uniform size (400 µm) in the weight fraction of 5%, 10%, and 15%. For Al-SiC composite material, Al356 alloy powders are mixed with SiC in the weight fraction of 5%, 10%, and 15%. Moisture in the particles is evaporated by adding the particle reinforcement into the matrix early in the process, before it disperses into the molten metal matrix. As a result, the wettability between the reinforcement particles and the metal matrix improves [5]. All the samples are melted in the furnace for 2 hours at 700°C. The molten metal is stirred using a stirrer with a simple paddle [6] as an agitator. The molten composite is then left to solidify on the ceramic plate inside the furnace. The solidified cast material is shown in Fig. 1(a). The composite block is then machined and cut into desired specimen test samples as seen in Fig. 1(b).

![Fig. 1(a) Solidified cast Al-Al$_2$O$_3$ composite material (b) Specimen of Al-Al$_2$O$_3$ composite materials for testing](image)

The mechanical properties of matrix and reinforcement particles are shown in Table I.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Aluminium Oxide</th>
<th>Silicon Carbide</th>
<th>Aluminium Alloy 356</th>
</tr>
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</tbody>
</table>

TABLE I
Table II indicates that the density of the material sample increases as the amount of particulate reinforcement increases [10]. This is expected as the density of the particulate is higher compared to that of the matrix material. It is observed that the tensile strength and strength-to-density ratio increase significantly with the increase of reinforcement particles.

It is also shown that the coefficient of thermal expansion (CTE) decreases with the increase of reinforcement particles. CTE measures the fractional change in volume per degree change in temperature. For automobile application, where variation of temperatures is present, a smaller CTE value of the material is preferred [7].

It should be noted that the properties obtained analytically are to be considered as ideal cases with the assumption that the distribution of the particles in the mixture is homogeneous and perfect bonding exists between the matrix metal and the reinforcement particles during the stir casting process. But in reality, there may likely to be flaws in terms of homogeneity of the distributed particles. Due to poor stirring, clustering and segregation of the reinforcement particles may occur, resulting in poor bonding between the particles and the metal matrix during the manufacturing process.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Density

The results obtained are comparable to the theoretical results. From Table III, it is observed that aluminium metal matrix composites with aluminium oxide (Al₂O₃) as particle reinforcements have higher density values compared to Aluminium metal matrix composites with Silicon Carbide (SiC) as particle reinforcements, since the density value for aluminium oxide (Al₂O₃) is relatively higher than that of silicon carbide (SiC). However, the proposed composite materials are significantly lighter than grey cast iron of density 7.2g/cm³.

B. Hardness and Tensile Strength

The Rockwell hardness test is conducted using a steel sphere of 1/16” diameter as an indentor. The conversion from Rockwell hardness to Brinell hardness number is obtained by using the standard conversion scale [7].
Tensile strength obtained from Brinell hardness values using the equation 5 are shown in Table IV.

\[
\text{Tensile strength (}\sigma\text{)} = 3.45\times \text{Brinell Hardness (HB)} \quad (5)
\]

### Table IV

<table>
<thead>
<tr>
<th>Composition with Al₂O₃ wt%</th>
<th>Rockwell Hardness (HR)</th>
<th>Brinell Hardness (HB)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Al</td>
<td>25</td>
<td>70</td>
<td>241.5</td>
</tr>
<tr>
<td>Al with 5%Al₂O₃</td>
<td>31</td>
<td>76</td>
<td>262.2</td>
</tr>
<tr>
<td>Al with 10%Al₂O₃</td>
<td>40</td>
<td>80</td>
<td>276.0</td>
</tr>
<tr>
<td>Al with 15%Al₂O₃</td>
<td>42</td>
<td>82</td>
<td>282.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition with SiC wt%</th>
<th>Rockwell Hardness (HR)</th>
<th>Brinell Hardness (HB)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al with 5%SiC</td>
<td>30.0</td>
<td>75.0</td>
<td>258.8</td>
</tr>
<tr>
<td>Al with 10%SiC</td>
<td>45.0</td>
<td>85.0</td>
<td>293.3</td>
</tr>
<tr>
<td>Al with 15%SiC</td>
<td>50.0</td>
<td>90.0</td>
<td>310.5</td>
</tr>
</tbody>
</table>

Table IV shows that Al-SiC composites exhibit relatively higher hardness and tensile strength compared to Al-Al₂O₃ composite materials for 10% and 15% particle reinforcements. A comparison of theoretical and experimental tensile strength for Al-Al₂O₃ composite material is presented in Fig. 2. The highest percentage difference of tensile strength between theoretical and experimental values is observed to be 11.83% for MMC with 10%wt of Al₂O₃. The lowest percentage difference is 5.92% for 100% Aluminium without any reinforcement particles. Al. In fact, in the composites, the reinforcement particles act as a strengthening agent that helps to fill in pores in the metal matrix, thus creating a stronger bond between the matrix’s particles.

With the stronger bond between particles, the mechanical properties of the material will also improve [10].

Fig. 2 Tensile strength comparison for MMC with Al₂O₃ reinforcements

### C. Wear Rate

Wear behaviour for the particle reinforced aluminium matrix composites are obtained by using the wear test. The test is conducted by applying a constant load of 10N onto the specimen while the specimen is in contact with a 600 grit SiC adhesive paper at 300 rpm and 400 rpm grinding speeds for a fixed time period of 5 minutes. The specimen mass is obtained before and after the wear test to measure the mass loss (M) to find the wear rate using the equation below:

\[
W = \frac{M}{\rho D} \quad (6)
\]

where
- \(W\) = Wear rate (mm³/m)
- \(M\) = Mass loss (g)
- \(\rho\) = Density (g/mm³)
- \(D\) = Sliding distance (m)

From Tables V to VIII, it is observed that (a) the wear rate increases with the increase of grinding speed (rpm), (b) aluminium metal matrix composites with SiC as reinforcement particles have lower wear rates compared to aluminium metal matrix composites with Al₂O₃ reinforcement particles, and (c) the wear rate decreases significantly with the increase of particle reinforcements for both type of composite materials. For instance, the wear rate for Al with 15% SiC composite is significantly lower than the wear rate for Al with 10% SiC composite.
only 0.126 mm³/m which is about 50% of the wear rate of 1005 Al (0.255 mm³/m).

D. Microstructure of Al-Al₂O₃ Composites

Microscopy of different composites materials such as Al+5wt%Al₂O₃, Al+10wt% Al₂O₃, Al+15%Al₂O₃ and Al 356 alloy are shown in Fig. 3 (a-d). One of the most important considerations in the fabrication of metal matrix composites (MMCs) materials is the uniform dispersion or distribution of the reinforcement particles as highlighted earlier. In Figure 3a, the microstructure of aluminium Al356 alloy is shown, with no reinforcement particles. In Fig. 3b, 3c, and 3d, the reinforcing particles of Al₂O₃ are clearly visible as white specks. In Fig. 3d, uniform distribution of Al₂O₃ particles is achieved. On the other hand, distribution of reinforcement particles is not uniformly achieved in Fig. 6b and 6c. Some minor clustering and segregation of particles is seen in Fig. 6d. Non uniform distribution of the particles can be a result of poor stirring of the particles into the metal matrix during the fabrication process. Segregation of particles may also occur during the solidification of the composite, when the Al dendrites solidify first, thus rejecting the particles by the solid-liquid interface, causing segregation of inter-dendritic region.

![Fig 3 Optical micrograph of alloys and composites (x35)](image)

(a) Aluminium at pure state (b) 5wt% Al₂O₃ reinforcement (c) 10wt% Al₂O₃ reinforcements (d) 15wt% Al₂O₃ reinforcement

V. CONCLUSION

The following conclusions can be drawn from the present study:

1. The proposed composite materials exhibit coefficients of thermal expansion as low as 4.6 x10⁻⁶/°C.
2. The composite materials achieve significant improvement in hardness and tensile strength compared to Al 356 alloy. For instance, the tensile strength of Al with 15% SiC is 23.68% more than that of 100% pure Al.
3. The composite materials show significantly higher strength to weight ratios compared to 100% Al. For instance, Al with 15% SiC exhibits strength to weight ratio of 1.74. The corresponding values of strength to weight ratios for 100% Al and cast iron are 1.54 and 0.765 respectively. Therefore, the proposed composite materials can be applied as potential lightweight materials in automobile components.
4. It is found experimentally that the wear rate decreases significantly with the addition of reinforcement particles. Al-SiC composites exhibit lower wear rate compared to Al-Al₂O₃ composites.

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