Dry Sliding Wear Behavior of Composite Materials Fabricated by Powder Metallurgy

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ABSTRACT: Aluminum matrix composites (AlMCs) were fabricated by powder metallurgy route. Two different ceramic oxides as (SiO2 and TiO2) were incorporated into aluminum matrix with different weight percentages at (3, 6, 9 and 12 wt. %) to produce aluminum matrix composites (AlMCs). There are many applications for aluminum matrix composites, such as connecting rods, vehicle parts and aerospace. The samples for this work were prepared by the following stages. The first stage is preparing aluminum powder (as a matrix) having 100 μm particle size, while SiO2, TiO2 as additive materials have about 150 μm in a particle size. The second stage is mixing the chosen powders using a planetary mixer. The third stage is a compacting process by a hydraulic unidirectional press to produce green compacts. Afterward, the samples were sintered at 480°C for 4 hours using an electrical furnace supplied with argon gas. The microstructure of the samples was examined using optical microscope (OM), the hardness of the samples was tested by Rockwell hardness apparatus. Wear test was carried out using pin-on-disc technique by changing the applied loads at a constant sliding time (10 min). Also, the physical properties, like porosity and density for the specimens after sintering were defined. The obtained results manifested that the improving in the wear resistance and hardness for Al/TiO2 is more than for Al/SiO2. And, the microstructure examination revealed that SiO2 and TiO2 are homogeneously distributed in Al matrix. Also, the results evinced an improvement in density and porosity for the manufactured composite material.

KEYWORDS: Composite material, Powder metallurgy, Microstructure, Density, Porosity, Hardness, Wear.

INTRODUCTION

Aluminum alloys are used widely in the automotive, electronics, aerospace and aeronautical applications. These applications need unique properties such as good mechanical and electrical properties, superior strength to the weight, high corrosion and wear resistance. To improve these properties, aluminum and its alloys must be reinforced by ceramic materials such as oxides, carbides or nitrides to obtain aluminum matrix composites (AlMCs) [1, 2]. AlMCs involves combination between Al matrixes with the additive material as the reinforcement. There are many types of materials used as reinforcement materials such as particulates, fibers and whiskers in the manufacturing of aluminum matrix composites (AlMCs) [3]. However, increasing the hardness of the product from ceramic reinforcement materials will lead to many difficulties during machining or cutting of the manufactured composites. Thus the ceramic reinforcement materials must be added at accurate portions to enhance mechanical and thermal properties of the products of aluminum matrix composites (AlMCs) [4]. Ceramic materials commonly used as reinforcements are TiC, SiC, Al2O3, SiO2, Y2O3 and TiO2 particulate ceramic materials affected more than fiber reinforcement materials on the physical and mechanical properties [5].

The size and shape of the ceramic particles and manufacturing processes of AlMCs affected on the tribological and mechanical properties. Many techniques are used to manufacture the AlMCs reinforced with ceramic particles by good bonding and homogeneously distributed in aluminum matrix. There are two methods are used to manufacture AlMCs, casting method and powder metallurgy method [6]. But at the same times, these methods included various defects, such as inclusions, voids, brittle intermetallic, porosity which make the ceramic particles distributed non-homogeneously in the matrix. Also, dislocations perhaps created in aluminum matrix composites as a result of the differences in thermal coefficient of each the matrix and reinforcement materials [7]. These imperfections lead to diminish the tribological and mechanical properties and then decrease the performance of AlMCs through the service. Furthermore, the wettability of ceramic particles in aluminum is low which leads to decrease the interfacial bonding between the ceramic particles and aluminum matrix, hence limit the load capacity
of AlMCs. Aluminum matrix composites are considered as metal matrix composites MMCs. Metal matrix composites MMCs depend on aluminum alloys have a greater attention owing to their properties enable it to use for different engineering applications [8].

However aluminum matrix composites AlMCs are extensively dependent on the characteristics of reinforcement, matrix and the interfaces between them, which are affected on the mechanical and thermal properties [9]. The characteristics of AlMCs are commonly distinguished by the microstructure of matrix whence the chemical composition, lattice imperfections and grain size. While the reinforcement is characterized by its concentration, distribution and size, which in turn affected on the mechanical and thermal properties, performance of the resultant composites and cost. Also the process used to fabricate AlMCs must be considered in account. There are many processes used to fabricate AlMCs, especially powder metallurgy and casting methods. Since casting method associated with many difficulties in manufacturing and resulted in various defects, hence the powder metallurgy is preferred than casting method [10]. There are many researches have been published about aluminum reinforced by ceramic materials.

Akash Mayurbhai et al. [11] studied the effect of fly ash on mechanical properties and sliding wear behavior of aluminum matrix composites using casting rout. Fly ash added by different weight percentages at 5, 10, 15, 20 and 25wt. %. The results of this work show that improving in mechanical properties and wear resistance of Al-10% fly ash. While B. Venkatesh and B. Harish [12] investigated the mechanical properties of aluminum matrix reinforced by SiC particles using powder metallurgy route. The results of this work revealed that SiC homogeneously distributed in Al matrix with little amount of porosity, and improving the mechanical properties. Whilst A. Thangarasu et al. [13] reported mechanical properties, sliding wear behavior and microstructure of AA6082/ TiC composites using friction stir processing (FSP). The results of this investigation shower that improving in wear resistance and mechanical properties such as micro hardness and ultimate tensile strength of the manufactured composites. The aim of the present investigation is to study the influence of TiO2 and SiO2 micro particles on the physical properties, hardness and sliding wear behavior of AMMCs synthesized by powder metallurgy technique.

METHODS AND MATERIALS

The used materials

Aluminum AA6061 powder was used as a matrix having 100 µm particle size, and the reinforced ceramic materials were SiO2 and TiO2 having 150 µm particle size. Tables 1(A) and (1B) show the chemical composition of the used AA6061 matrix [14] and its mechanical and physical properties, respectively, while Table 2 depicts the mechanical and physical properties of SiO2 and TiO2 [15].

Table 1(A). Chemical composition of AA 6061 matrix (wt. %).

<table>
<thead>
<tr>
<th></th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Cr</th>
<th>Cu</th>
<th>Zn</th>
<th>Ti</th>
<th>Mn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.83</td>
<td>0.61</td>
<td>0.22</td>
<td>0.21</td>
<td>0.21</td>
<td>0.1</td>
<td>0.09</td>
<td>0.02</td>
<td>Rem.</td>
</tr>
</tbody>
</table>

Table 1(B). Mechanical and physical properties of Al6061 matrix [14].

<table>
<thead>
<tr>
<th></th>
<th>Max. Tensile Strength (MPa)</th>
<th>Hardness (HB500)</th>
<th>Elastic Modulus (GPa)</th>
<th>Density (g/cc)</th>
<th>Poisons ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>115</td>
<td>30</td>
<td>70-80</td>
<td>2.7</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table 2. Mechanical and physical properties of TiO2 and SiO2 [15].

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive Strength (MPa)</th>
<th>Hardness (MPa)</th>
<th>Elastic limit (MPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>Density (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>1100-1600</td>
<td>4500-9500</td>
<td>45-155</td>
<td>66.3-74.8</td>
<td>0.15-0.19</td>
<td>2.17-2.65</td>
</tr>
<tr>
<td>TiO2</td>
<td>660-3675</td>
<td>9330-10290</td>
<td>333.3-367.5</td>
<td>230-288</td>
<td>0.27-0.29</td>
<td>3.97-4.05</td>
</tr>
</tbody>
</table>

Specimens preparation

Preparing the samples was done using the powder metallurgy route by mixing the chosen powders with an activator (zinc stearate). The mixing process was performed by planetary mixer with steel milling balls having 1 cm diameter and at 250 rpm for 4 hours. Afterward, the mixture of the powders was compacted in uniaxial hydraulic press according to the ASTM-D 618 using punch-die set assembly to produce green compacts, and the samples were weighed by accurate balance to measure the density after sintering. The compacting process was followed by sintering the samples in an electrical furnace at 480°C for 4 hours, supplied with argon gas to prevent the oxidation of samples. After the sintering process, the density was calculated through dividing the weight in (g) of the sample by the volume in (cm³).

Microstructure examination

Before microstructure examination by optical microscopy (OM), the samples (AA6061/SiO2 and AA6061/TiO2) were ground using emery papers having 500 and 1000 µm particle size. After the grinding process, the samples were first polished using a polishing device with diamond paste with 0.7 µm particle size for 15 min and then etched using a suitable reagent (1% Keller) for 0.5 min.

Density test

Theoretical density of (Al/SiO2 and Al/TiO2) was determined using Archimedes principle according to (ASTM C20-00) by the following formulas [16]:

For Al/SiO2 \( \rho_c = \frac{\frac{1}{\rho_{Al}} + \frac{w_{SiO2}}{\rho_{SiO2}}}{\frac{w_{Al}}{\rho_{Al}} + \frac{w_{SiO2}}{\rho_{SiO2}}} \) (1)

For Al/TiO2 \( \rho_c = \frac{\frac{1}{\rho_{Al}} + \frac{w_{TiO2}}{\rho_{TiO2}}}{\frac{w_{Al}}{\rho_{Al}} + \frac{w_{TiO2}}{\rho_{TiO2}}} \) (2)

Also, the actual density for all samples after sintering was computed by the following equation [16]:

\( \rho_s = \frac{m_a \times \rho_w}{m_a - m_w} \) (3)

While, the porosity of the samples was measured using the following equation:

\( \text{porosity} \% = 1 - \frac{P_s}{P_{th}} \) (4)

Hardness test

Hardness test was performed by the Rockwell hardness apparatus type (Wilson Hardness apparatus, Model: 2481 T, USA) by (B) scale with the applied load of indenter (100 Kg). This test was conducted for the all samples before and after sintering. For each sample, four readings were taken to calculate the average diameter.

Wear test
Wear test was carried out by the pin-on-disc technique for the sintered samples according to ASTM-G99 standard. The dimensions of the wear sample are 1 cm in diameter and 2 cm in height. This test was achieved by changing the loads at 2, 4, 6, 8 and 10 N at constant time (10 min). The wear rate was calculated using the weighing method, by measuring the loss of weight for all sintered samples using the sensitive electronic balance having an accuracy of (0.01 mg). Then, the wear rate was computed by the following equation [17]:

\[
wear \ rate = \frac{\Delta w}{2\pi r n t} 
\]  
(5)

\[
\Delta W = W_1 - W_2
\]  
(6)

\[
S.D = 2\pi r n t
\]

Where:

\(\Delta W\): The change in the weight (g)
\(W_1\) and \(W_2\): The weight of sample before and after the wear test, respectively (g)
\(r\): The radius of rotating (mm)
\(n\): The number of disc rotations (rpm)
\(t\): The time of test (min)

RESULTS AND DISCUSSION

Microstructural analysis

Photomicrographs of Al/SiO\(_2\) and Al/TiO\(_2\) composite materials displayed that the additive particles of SiO\(_2\) and TiO\(_2\) distributed homogeneously in AA 6061 matrix with a little amount of porosity as a result of sintering process, as shown in Figure (1). The homogeneity of distribution of SiO\(_2\) and TiO\(_2\) in AA 6061 matrix is due to the mixing action and the time of mixing process.
Figure 1. Images of Al/SiO\textsubscript{2} and Al/TiO\textsubscript{2} samples for different weight percentages. (250 X)

Characteristics of compacting and sintering

In compacting process, the additive SiO\textsubscript{2} and TiO\textsubscript{2} particles will increase the green density because the condensation will occur in compacting, and all particles will close together as the increasing in the force of pressing. While in sintering, thermal welding will occur between all particles of powder mixture and form necking between the particles, which in turn create shrinkage for the sintered samples and improve the sintering density \[18\]. The temperature of sintering process will create strong bonding between the matrix and additive particles, improving the mechanical properties, such as hardness, yield strength and tensile strength. Also, these bonding forces affected on the wear resistance of the composite materials, which in turn increase the dislocations density and create dislocation loops around the additive particles which prevent them to move \[19\]. In fact, the increasing of weight percentage of the additive materials will decrease the density of the prepared composite materials, as depicted in Figure (2) which causes to decrease the wettability between the additive materials (SiO\textsubscript{2} and TiO\textsubscript{2}) and aluminum matrix. Also, the porosity will be created at the interfaces between SiO\textsubscript{2}, TiO\textsubscript{2} and matrix, and then the density for composite material Al/SiO\textsubscript{2} is more than for Al/TiO\textsubscript{2}. While the porosity increases with the increasing of each SiO\textsubscript{2} and TiO\textsubscript{2}, at the same time, the porosity for Al/SiO\textsubscript{2} composite material is more than for Al/TiO\textsubscript{2}, as shown in Fig. (3), this is related to the density for these composite materials.

Figure 2: Theoretical and experimental densities versus the wt.% of TiO\textsubscript{2} and SiO\textsubscript{2}
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Wear behavior analysis

Wear resistance of Al/SiO₂ and Al/TiO₂ composite materials is extensively dependent on the additive particles and their weight percentages. The increasing in the weight percentage of SiO₂ and TiO₂ causes to increase the wear resistance (decreasing wear rate), this is attributed to the bonding (reaction) between the additive materials and the aluminum matrix, which will create thermal stresses between them since the melting temperatures between the additive materials and matrix are different, and in turn, these stresses will increase the density of dislocation. The additive particles will hinder the moving of dislocation and decreasing the wear rate (increasing wear resistance). Figure (4) illustrates that the increasing of TiO₂ decreases the wear rate more than for SiO₂, and this is agreed with [20]. Increasing the applied loads leads to increase the wear rate due to the rise of heat temperature between the rotating disc and the pin (Al/SiO₂, Al/TiO₂) and then creates oxidation layers, which break and form grooves as worn surfaces, as agreed with [21]. There are many investigations studied the effect of additive materials on the wear rate of aluminum matrix [22]. Figure [4] demonstrates the relationships between wear rate and applied loads for different percentages of additive materials. The increasing of applied load will increase the wear rate for the all samples at constant time, the wear rate of composite materials reinforced with TiO₂ is lower than for SiO₂ and lower than for Al matrix.

Figure 3. Porosity (%) versus the wt.% of TiO₂ and SiO₂

![Graph showing porosity vs TiO₂ and SiO₂ weight percentage]
The surface topography of the composite materials was examined using the optical microscopy (OM). Figure (5) views the grooves of worn surfaces for composite material Al/SiO2 and Al/TiO2 composite materials. The grooves of composite material (Al/TiO2) are finer than those for the composite material (Al/SiO2), because the TiO2 particles are harder than the SiO2 particles.

Figure 5. Images of the worn surfaces of Al/SiO2 and Al/TiO2 at (6N).

Hardness characteristics

Hardness characteristics of the manufactured composite material are extremely dependent on the amount and particle size of additive material. The increasing in the weight percentage of SiO2 and TiO2 will increase the dislocations density and then increase the hardness. The hardness of Al/TiO2 is higher than that for Al/SiO2, since
the TiO2 additive material creates a stronger bonding with Al matrix than the SiO2 additive material, then obstructs the moving of dislocations and finally increases the hardness, as revealed in Figure (6).

![Graph showing relationship between hardness and TiO2 and SiO2 content.](image)

**Figure 6.** Relationships between Rockwell Hardness Number and the wt.% of SiO2 and TiO2.

**CONCLUSIONS**

In this work, AA606/ SiO2 and AA6061/ TiO2 AlMCs were manufactured by powder metallurgy route. Dry sliding wear behaviors of AA6061/ SiO2 and AA6061/TiO2 composites were studied; wear resistance improved extensively by the addition of TiO2 particles. The conclusions of the present work are summarized based on the results as the following:

1. Photomicrographs of optical microscopy showed a homogeneous dispersion of SiO2 and TiO2 particles in AA6061 matrix.
2. The hardness of AlMCs increased with increase in weight percentage of SiO2 and TiO2. The increment in hardness for Al/TiO2 is higher than for Al/SiO2.
3. Theoretical density and % of porosity decrease with the increase of weight percentage of SiO2 and TiO2.
4. The wear rate increased with increase in applied load. Wear rate for AA6061/ TiO2 lower than for AA606/ SiO2.
5. The wear resistance of AlMCs increased with increase in weight percentage for TiO2 more than for SiO2.

**REFERENCES**


