Effect of Alumina Particles Addition on Physico-Mechanical Properties of AL-Matrix Composites

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ABSTRACT

Metal-matrix composites (MMCs) are attracting considerable interest worldwide because of their superior mechanical and tribological properties. This study describes multifactor-based experiments that were applied to research and investigates Aluminum matrix composite reinforced with 5, 10 & 15 wt% Alumina particles. Mechanical mixing technique was used for fabrication. Sintering was carried out in a vacuum furnace at 600°C for 1 hr. The effects of Alumina percentage on the density, microstructure, both electrical & thermal conductivities, hardness and compression strength was investigated. The results showed that sample containing 5 wt% Alumina is near-fully dense. Also it has the highest hardness and compression strength.

Keywords: Al matrix Composites; Alumina Reinforcement; Mechanical Mixing; Thermal Conductivity; Electrical Conductivity; Mechanical Properties

1. Introduction

In the last decades, there is an increasing trend towards using composite materials, in order to achieve better performance in engineering materials [1]. Applications of AL-based metal matrix composite continue to expand for structural applications. Particularly in aerospace and automotive industries, owing to their low density, high thermal conductivity, high specific strength, stiffness, and better wear resistance resulting in considerable economic advantages [2-9]. Aluminum alloy has disadvantages as low hardness and poor wear resistance which are the main obstacles for their high performance tribological applications [10,11]. Addition of ceramic oxide such as alumina reinforcement into ductile matrix such as Al affects greatly on both mechanical and physical properties of the produced composite [12-18]. During the last decades, enormous researches focused on hard ceramic particulate, fiber and whiskers reinforced aluminum metal which causes a modification of strength, stiffness, hardness, wear and fatigue resistance specially at elevated temperature applications. Those particularly improves corrosion resistance of the material, compared with conventional aluminum alloy [19-22]. The aim of this study is how to obtain a composite material of AL matrix with a uniform distribution of ceramic particles. Al₂O₃ is the most popular ceramic oxide that can be used as reinforcement due to its high stability at elevated temperatures that prevents its reaction with AL matrix [1]. There are several methods for fabrication of the Metal-Matrix Composites including mechanical milling, vortex process and ultra sonic cavitations, but all of these techniques are expensive because they need more energy. Powder metallurgy is a good technique in producing MMCs. Its main advantage is the low processing temperature than the melting technique, so there is no interaction between the matrix and the reinforcement. Also high homogenization between the two phases is achieved [23]. Another advantage is the fabrication of a near net shape product with low cost [24]. In this research, mixing of AL powder and Al₂O₃ particles was achieved and a uniaxial pressed was used to produce the composite samples. Physico-mechanical properties of the produced composites were investigated.
2. Material and Experimental Procedures
2.1. Mixing, Cold Compaction and Sintering

In this research, AL powder with purity 99.99% and particle size 5 - 10 µm was used as a matrix and reinforced with 5, 10, and 15 wt% of AL₂O₃ with 10 µm particles size. Aluminum and alumina powders were investigated by SEM of model JOEL-JSM-4510, Development XRD diffractometer model Burcker D8 Advance with Ni filtered and Cu target in Central Metallurgical Research Institute (CMRDI) in Cairo. The powders were mixed with 0.5 wt% paraffin wax as a lubricant to reduce friction during compaction and liquid acetone was used as a process control agent, then dried at 80°C for 30 min and cold compacted at room temperature in a uniaxial press at 1060 Mpa. The samples were sintered in a vacuum furnace at 600°C for 1 hr and a heating rate of 10°C/min.

2.2. Composite Characterization

Relative densities of the sintered samples were measured using Archimedes method using water as a floating liquid according to MPIF standard 42, 1998, in which the sintered specimen was weighed in air and in distilled water then the density (D) was calculated according to the following equation:

\[ D = \frac{W_a}{W_a - W_w} \quad \text{g/cm}^3 \quad (1) \]

Where, 
W_a and W_w are the masses of the sample in air and water respectively. The theoretical densities (D_th) for the investigated materials were calculated according to the following equation:

\[ D_{th} = \left( V_{Al} \times D_{Al} \right) + \left( V_{Al_2O_3} \times D_{Al_2O_3} \right) \quad \text{g/cm}^3 \quad (2) \]

Where, 
V_{Al_2O_3} is the volume fraction of alumina reinforcement,
D_{Al_2O_3} is the density of AL₂O₃ equal 3.95 g/cm³,
V_{Al} and D_{Al} are the volume fraction and density of the AL powder respectively. The degree of porosity of the sintered compacts was calculated according to the following equation:

\[ \text{Porosity} \% = \left( D_{th} - D_a \right) / D_{th} \% \quad (3) \]

Where, 
D_{th} is the theoretical density of the sintered sample and D_a is the actual density. Microstructure investigation was performed using both optical and scanning electron microscope using a JEOL JSM 5410-microscope. The diffraction patterns of the sintered samples were achieved by x-ray diffraction analysis using x-ray diffractometer model x-pert PRO PANalytical with Cu kα radiation (λ = 0.15406 nm) The electrical resistivity of the sintered materials was measured using the four-probe method using Omega CL1084 multimeter device, where the outermost two contacts were for passing D.C. current & the inner two contacts were for measuring the potential difference.

A fixed DC current of one ampere was passed through the sample via two crocodile clips. For each test the multimeter was zeroed with no current passing the specimen, and then the measurement was carried out. The resistivity (ρ) was calculated according to the following equation:

\[ \rho = \frac{R \cdot A}{L} \quad (4) \]

Where,
R is the resistance in mΩ, L is the measured length in cm and A is the cross section area in cm². The thermal conductivity of the composites was derived from the Wiedemann-Franz Law, which links the thermal conductivity to the electrical conductivity according to the following equation:

\[ K / \sigma = L \cdot T \quad (5) \]

Where, 
K is the thermal conductivity in W/mK, T is the absolute temperature in K, \( \sigma \) is the electrical conductivity in \( \Omega^{-1} \cdot \text{m}^{-1} \), and L is the Lorenz number, equal to 2.45 × 10⁻⁸ WΩ⁻¹K⁻². Electrical conductivities of the polished samples were determined from the electrical resistivity measurements. The size of the samples used for testing is 32 mm × 11 mm × 4 mm size. The electrical resistivity measured using Omega micro-ohmmeter in the two-probe mode. Vickers micro hardness was measured as the average of 5 readings along the cross section surface of the specimen using Vickers hardness tester by applying 4.9 N load and load time 10 sec. Compression strength test of investigated samples was also measured using uniaxial SHIMADZU universal testing machine UH-F500KN. The applied cross-head speed of universal test machine used in this study is 2 mm/min. The test was conducted at room temperature (25°C).

3. Results and Discussion
3.1. Powder Characterization
(Figures 1(a) and (b)), show the experimental results of the XRD pattern of pure AL and AL₂O₃ powders respectively, which indicate the appearance of AL and AL₂O₃ peaks with high intensity that indicates the purity of the raw materials. (Figures 2(a) and (b)), show that the particle diameter of AL and AL₂O₃ was 5 - 10, and 10 µm respectively.

3.2. Composite Characterization
3.2.1. X-Ray Diffraction Analysis
X-ray diffraction was performed to determine the phase
structure of the composites. Figure 3 show the XRD pattern of 5, 10 and 15 wt% AL2O3.

It can be seen that the sintering process did not produce any new phases rather than face centered cubic structure with space group Fm-3m, a = 0.40494 for AL and corundum hexagonal bravais lattice, space group R3m, a = b = (3.079) and c = (67.996 nm) for AL2O3 this means that the phases indicated by XRD analysis were similar for the three composites. The XRD pattern indicated that as the AL2O3 percent increases the intensities of the peaks that belongs to AL2O3 was increased and that of AL was slightly decreased. So from XRD charts there is no solid state reaction between Al and AL2O3 during the sintering process.

3.2.2. Density
Relative density of the composite is the ratio of the measured sintered density to the theoretical one. It was determined for pure Al and AL-AL2O3 composites. The values of the relative density of 5, 10 & 15 wt% AL-
AL₂O₃ composites are shown in Table 1. This Table shows that the theoretical density increases by increasing the AL₂O₃ percent.

This can be attributed to the higher density of AL₂O₃ more than Al. Figure 4 indicates the experimental results for studying the relation between the relative density and alumina content. From this figure, the bulk density of 5 wt% AL₂O₃ was about 96.5% which is near fully density. This may be rationalized by the near ratio between the volume fraction of 5 wt% AL₂O₃ and that of 95% Al. By increasing the AL₂O₃ percent the density decreases, this is due to the higher hardness of AL₂O₃ than that of Al. It acts as a barrier network against consolidation that prevents the densification of the particles. Also increasing the AL₂O₃ percent leads to more contact between AL-AL₂O₃ particles and so more intensive form appear [25]. The experimental results for investigating the relation between porosity and alumina content are shown in Figure 5. From this figure, the porosity of AL-AL₂O₃ composites where 5 wt% AL₂O₃ recorded 3.5% this mean that this sample is near full dense with higher density compared with the other samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Sintering Density</th>
<th>Theoretical Density</th>
<th>Relative Density %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% AL₂O₃</td>
<td>2.648</td>
<td>2.74</td>
<td>96.5</td>
</tr>
<tr>
<td>10% AL₂O₃</td>
<td>2.642</td>
<td>2.78</td>
<td>94.7</td>
</tr>
<tr>
<td>15% AL₂O₃</td>
<td>2.596</td>
<td>2.83</td>
<td>91.6</td>
</tr>
</tbody>
</table>

3.2.3. Microstructure of the Sintered Samples

In order to study the micro structure changes of AL matrix by mixing with AL₂O₃ particles, both optical and scanning electron microscopes (SEM) were used. Figures 6(a)-(c) show the optical micrographs of AL-AL₂O₃ sintered samples with 200× magnification.

Alumina particles are homogenously distributed all over the Al matrix. This may be due to the suitable mix-
ing technique, time of mixing, compaction and suitable sintering temperature. SEM micrographs of pure Al & Al-Al$_2$O$_3$ samples were shown in Figures 7(a)-(d), with high magnifications and EDAX analysis for 10 wt% Al$_2$O$_3$.

It was observed that the spectrum of 10 wt% Al$_2$O$_3$ shows the presence of Al and oxygen elements which indicates that Al$_2$O$_3$ particles are dispersed into Al matrix with no other contamination. Both optical and SEM micrographs shows the homogeneous dispersion of Al$_2$O$_3$ in the Al matrix for the three Al-Al$_2$O$_3$ composites. The micrographs contains three phases one of them is the gray matrix which is the Al matrix and the dispersed phase is the white spots which represents the Al$_2$O$_3$ particles and the third phase is the black spots that is the pores in the sintered samples which was performed by EDAX. Addition of more Al$_2$O$_3$ than 5 wt% causes the increasing of the internal porosity. This can be attributed to the poor wettability between the Al matrix and Al$_2$O$_3$ which causes aggregation of Al$_2$O$_3$ particles that distinct obstructed densification creating gaps that prevents the complete densification of the particles. The increasing of porosities is dark point which affects greatly on the mechanical properties such as hardness & compression.

Figure 6. Optical micrographs of: (a) AL-5 wt% Al$_2$O$_3$; (b) AL-10 wt% Al$_2$O$_3$; and (c) AL-15 wt% Al$_2$O$_3$.

Figure 7. SEM Micrographs for (a) AL; (b) 5 wt% Al$_2$O$_3$; (c) 10 wt% Al$_2$O$_3$; and (d) 15 wt% Al$_2$O$_3$. 
3.2.4. Electrical Resistivity Measurement
In this investigation, the electric resistance of the investigated samples was measured and converted to the electrical conductivity according to the ASTM standard B193-72. Figure 8 and Table 2 show that the electrical resistivity increases by increasing the Al₂O₃ percent.

This is according to the lower conductivity value of Al₂O₃ more than that of Al that restricts the motion of the electrons which are responsible for the conductivity. Also the high porosity of the higher Al₂O₃ percent samples resulted from the weak bond and non-wettability between Al and Al₂O₃ creates voids that decrease the motilities of the free electrons causing a high resistivity [26].

3.2.5. Thermal Conductivity Measurement
Thermal conductivity is affected by many factors those are the conductivities of the constituents, reinforcement distribution, the volume fractions, shape & size of the components, the interaction between the two phases and the method of preparation. The experimental results for investigating the relation between thermal conductivity and alumina content are shown in Figure 9. From this figure, the thermal conductivity of the composite decreases by increasing the Al₂O₃ percent. Also thermal conductivity is directly affected by the porosity, since the conductivity of a pore is zero so by increasing the Al₂O₃ content the pores increases and the thermal conductivity decreases. The relation between porosity and thermal conductivity is given by the following equation [27].

\[ k = KS \left( 1 - F \right) \]  

(6)

Where,
- \( k \) is the thermal conductivity (w/mk),
- \( KS \) is the intrinsic thermal conductivity, and
- \( F \) is the fractional porosity. Also the nature of the ceramic Al₂O₃ particles that distort the structure forms barrier for the electrons which are responsible for thermal conductivities [28]. The values of Thermal conductivity for pure Al & 5, 10 and 15 wt% Al₂O₃ are shown in Table 3.

3.2.6. Hardness Measurements
Micro hardness of Al-Al₂O₃ composites were shown in Figure 10 from this figure, it was clear that 5% Al₂O₃ sample has the highest hardness due to the strengthening effect of the hard Al₂O₃ oxide ceramic, also the higher density and lower porosity of this sample. The presence of pores has a negative effect on the hardness. As the porosity of the samples increases by increasing alumina content the hardness decreases.

3.2.7. Compression Test Measurement
Figure 11 shows the results of compressive strength, from this figure it was evident that 5 wt% Al₂O₃ sample has the highest compressive strength value more than that of 10 & 15 wt% Al₂O₃. This can be rationalized by the lower porosity of this sample than the other ones, in

- Figure 8. Electrical conductivity of pure Al & 5, 10, and 15 wt% Al₂O₃ composites.
- Figure 9. Thermal conductivity of pure Al & 5, 10, and 15 wt% Al₂O₃ composites.
- Table 3. Thermal conductivity values for pure Al & 5, 10 and 15 wt% Al₂O₃.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Thermal conductivity * 10⁻² K = σ·L·T (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure</td>
<td>8.82</td>
</tr>
<tr>
<td>5% Al₂O₃</td>
<td>7.90</td>
</tr>
<tr>
<td>10% Al₂O₃</td>
<td>4.66</td>
</tr>
<tr>
<td>15% Al₂O₃</td>
<td>2.83</td>
</tr>
</tbody>
</table>

- Figure 10. Micro hardness values as a function of Al₂O₃ percent.
which the compressive strength increases by decreasing the porosity and increasing both the Al-content and density. The porosity of Al-Al$_2$O$_3$ composite increases by increasing Al$_2$O$_3$ content this is considered a suitable site for crack nucleation and growth where the stress may concentrate [29]. Figure 12 shows the compressive strength at 50% strain. From (Figures 11 and 12), the higher compression strength value was for 5 wt% sample which is in agreement with the above results.

4. Conclusions
According to the above mentioned results and discussions, it can be concluded that:
1) Mechanical mixing is a good technique for preparing Al-Al$_2$O$_3$ composite.
2) By this suggested technique in this research homogeneous distribution of Al$_2$O$_3$ particles into Al matrix was achieved.
3) Both the electrical and thermal conductivities of the samples decrease by increasing the Al$_2$O$_3$ percent.
4) 5 wt% Al$_2$O$_3$ sample has the lower porosity and higher density, also has the higher hardness and higher compression strength.

REFERENCES


