MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION OF 7075 ALUMINUM ALLOY REINFORCED BY ALUMINA (Al₂O₃) NANOPARTICLE DISPERSION

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ABSTRACT

Composites of 7075 aluminum alloy (Al7075) with Alumina (Al₂O₃) nanoparticles were prepared by casting. Behavior of Al7075 alloy and Al7075–Al₂O₃ nanocomposites produced by stir casting and hot consolidation were investigated. The samples were characterized by hardness test, pin-on-disk wear test, X-ray diffraction (XRD), scanning electron microscopy (SEM) and Atomic force microscopy (AFM). Nanocomposites containing 1.0wt% Al₂O₃ showed a maximum hardness of 134 HV and optimum wear rate of. Increasing the amount of Al₂O₃ up to 1.5wt% resulted in decrease in hardness values and a sharp rise in wear rate also the fracture toughness.

Keywords: MMC, 7075, Nanoparticles, Alumina, Stir Casting.

1. INTRODUCTION

The development of high strength Al alloys for use at moderate temperatures is of great interest for engineering applications. Aluminum alloys with strength improvement can be obtained by the dispersion of fine and homogeneous nanoparticles, which must be stabilized at medium–high temperatures [1]. During research to design such materials, the concept of composite materials was developed which can bring together the combined advantages of the constituent materials, something not possible when they are employed alone [2]. Metal matrix composites (MMCs) have emerged because of their high specific modulus, strength-to-weight ratio, fatigue strength, temperature stability and wear resistance [3]. Another important driving factor is the ability to tailor the mechanical and physical properties (such as the coefficient of thermal expansion by selecting the reinforcement type) and volume fraction, along with the matrix alloy. The term ‘nanocomposite’ is used when the dispersed phase is in the range of nanometers. Mechanical alloying and mechanical milling have emerged as alternative ways to produce nanocomposite materials, formed by nanoparticles dispersion into a metallic matrix [1,4]. The present study is focused on the possibility
of improving the properties of 7075 aluminum alloy by dispersing insoluble nanoparticles of Alumina (Al₂O₃) into the matrix by casting. Microstructural and mechanical characterization is presented and discussed. The wear tests were conducted with a pin-on-disk tribometer. In the wear test, a pin specimen was held with its axis perpendicular to the surface of a disk.

2. MATERIALS

The raw material used consists of aluminum alloy 7075 and high purity alumina powder. Alumina powder with approximately 20 nm was supplied by SSnano, USA. Different weight fractions of Al₂O₃ particles were mixed with aluminum. The weight fractions of Al₂O₃ in the samples are 0.5 wt%, 1 wt% and 1.5 wt%. Al-Al₂O₃. The alloy chemical composition was examined using SPECTRO metal analyze. The composition is given in table 1.

<table>
<thead>
<tr>
<th>Table 1 the chemical composition of Al 7075</th>
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<tbody>
<tr>
<td>Si</td>
</tr>
<tr>
<td>0.07</td>
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</table>

3. EXPERIMENTAL PROCEDURE

The composites were made by casting method using mechanical mixing of the molten matrix. At first step, 500 g of Al-7075 alloy was charged into the graphite crucible. The alloy was melted in a laboratory electric resistive furnace by heating up to 650 °C. After melting, cleaning of the melt from the slag was performed by overheating of the melt 50 °C above the liquid’s temperature. Mixing process was done by an impeller with a speed about 300 rpm at 650 °C in semi-solid condition. The impeller was designed to be able to make radial and axial forces in the melt. The slurry was stirred for 20 min. In the last stage, the slurry was poured in a 100x120x14 mm steel mold. Specimens from longitudinal section were cut and prepared by mechanical polishing and then hardness tests were taken from samples. Characterization of the produced composite samples included metallographic examination, hardness measurement and density determination. For microstructure study, the specimens were prepared by grinding through 600, 1200 and 2000 grit papers, respectively and then were polished with 3 µm alumina. The specimens were examined by Optical and Scanning Electron Microscopy (SEM). The amount of porosity was determined by comparing the measured density from Archimedes method with their theoretical density. The hardness values (Vickers hardness) of the samples were measured on the polished samples in 5 points for each sample.

4. RESULTS AND DISCUSSION

4.1 Density and Porosity Measurement

Relative density of the consolidated samples were measured by Archimedes water immersion method. The Al alloy 7075 and the reinforcement Al₂O₃ particles have the densities of 2.7 and 3.9 g/cm³, respectively. In order to determine the porosity content, density measurements were conducted on unreinforced and composites reinforced with 0.5, 1 and 1.5 wt. % nano-Al₂O₃ particles. The difference between the theoretical densities and calculated densities which were obtained are given in table 2.
Table 2 Theoretical and practical density

<table>
<thead>
<tr>
<th>Sample</th>
<th>Theoretical density (g/cm³)</th>
<th>Apparent or practical density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 %</td>
<td>2.7880</td>
<td>2.7810</td>
</tr>
<tr>
<td>1%</td>
<td>2.7925</td>
<td>2.7768</td>
</tr>
<tr>
<td>1.5 %</td>
<td>2.7921</td>
<td>2.7748</td>
</tr>
</tbody>
</table>

4.2 Microstructure Examinations

Optical photographs of the microstructure of the cast aluminum 7075 alloy reinforced with 0.5wt.%, 1wt% and 1.5wt% Al₂O₃, fabricated using the mixture of Al liquid state and nano-Al₂O₃ particles as reinforcement. It is assumed that the introduction of the mixture into particle-free matrices helps to disperse nanoparticles more uniformly which provides some heterogeneous nucleation sites during solidification, resulting in a more refined. however, at higher magnification, agglomeration is obvious especially for high fraction of nano particle reinforcement as shown in figure 1.

![Figure 1: Microstructures of aluminum with 1wt%. alumina](image1)

The Optical microstructure examination is shown that the percentage of porosity increase with increasing weight fraction of nanoparticles, as it is clear in figure 2. Even most effective precipitation heat treatment cannot eliminate all porosity from MMC unless the metal reaches its eutectic temperature and cooled with high cooling rate. 7075 AL alloy is very sensitive for cooling rate in heat treatment [5]. It is clear that the grain size range is about 70-200 µm, this grain size range indicates good mechanical properties. However, mechanical properties do not depend on grain size only, but also on the bonding between them [6]. Grain boundaries tend to enlarge with increasing Al₂O₃ wt. fraction due to movement of particles (if it dealt with as impurities )out of the grain during solidification stage [7].

![Figure 2: Microstructures of aluminum with 1.5wt%. Alumina](image2)
Figure 3 shows the (SEM) images for the three samples

![Image](a)

![Image](b)

![Image](c)

**Figure 3** (SEM) micrographs, (a)0.5%, (b)1%, (c)1.5%

It is clear from micrographs above that the alumina particles are well distributed. The particles cannot be considered as distributed regularly all over the matrix since these micrographs represent a small portion of the material. However, as stir casting technique is used, it can be successful technique applicable to industrial purposes and mass product. For more regular distributed and efficient particles, ultrasonic technique showed better result [8]. This technique is still costly high to be applicable in industrial and mass productions. Figure 4 shows SEM micrographs of
the as-cast Al–2%Al₂O₃ nanocomposites synthesized using ultrasonic technique. In 0.5% a pitting-like point appears. It is expected to be formed during solidification process as a result of clustering of alumina and entrap of gases by it, as well as the deference of thermal expansion between it and Al matrix. In 1.5% image it is clear that there are eutectic zones caused by precipitation of alumina particles on grain boundary during grain growth stage.

3.3 X-ray Diffraction Results

The XRD spectrum of Al 7075 with 0.5wt.%, 1% and 1.5% Al₂O₃ nanocomposite is shown in figure 5 (a,b&c). The diffraction patterns of the nanocomposite exhibit various peaks corresponding to the face centered cubic phase of Al. It appears that the addition of ultra-fine Al₂O₃ resulted in further broadening of Al peaks. X-ray diffraction peaks, which increased with an increase of fine Al₂O₃ content. The peak width of 1.5 wt.% Al₂O₃ nanocomposite was increased by around 25% higher than unreinforced nanocrystalline alloy. This indicated the formation of fine grain. Further, a minor shift (towards smaller angle) in the position of the XRD peaks was also noticed and this could be related to the dissolution of little oxygen atoms from alumina and other atoms like Mg, Cu etc. related to minor matrix alloying elements in the lattice.

(a) (b) (c)

Figure 5 XRD patterns

The XRD images show existence of alumina phase. Other phases also appear. They are logically oxides of other elements' oxides formed during casting as these alloying elements were molten and exposed to air in spite of relatively short stirring time. They are expected to degrade the
original alloy properties, specially mechanical ones. The highest peaks represent Al [8,9]. Third Image (1.5%) shows shifting of Al peak (Increased 2θ) that indicates coarser crystal size of Al at Burger’s vector (1,1,1) coordinates [10,11].

3.4 Atomic Force Microscope analysis

The morphological changes of the metal nanocomposites investigated by AFM and the AFM images are presented. Effect of nano-\(\text{Al}_2\text{O}_3\) surface treatment on the tribological performance of epoxy composite [12]. From Figure, it can be observed that the morphology Surface roughness is also an important parameter composite application. Surface roughness of the composite increase by increasing the volume fraction of the reinforcement. These results are further confirmed by AFM images, which show an increase in RMS roughness of the nanocomposite. It is widely established that addition of a nanocrystalline phase affects the rod-like structure and crystallite size, which determine the surface morphologies of the nanocomposite. Figure 6 for aluminum with 0.5% 20nm alumina, figure 7 pure aluminum.

These factors are believed to be responsible for changes in morphologies of the nanocomposite. This result is important because the rod-like morphology differs in terms of mechanical properties due to bonding strength between grains. The enhancement in the rod-like morphology is important for the excellent mechanical properties of the stable hard nanocomposites.

![AFM Images of 0.5% \(\text{Al}_2\text{O}_3\)](attachment:image)

(a)

![AFM Images of 0.5% \(\text{Al}_2\text{O}_3\)](attachment:image)

(b)

**Figure 6** AFM Images of 0.5% \(\text{Al}_2\text{O}_3\)
3.5 Hardness Test

Vickers hardness tester machine used for the hardness measurement. The surface being tested generally requires a metallographic finish. The result of Vickers hardness test for aluminum 7075 and aluminum 7075 with different volume fraction of alumina Al$_2$O$_3$ are shown in figure 10.

As observed from figure 8, the hardness value increases up to 134.33 with 0.5 volume fraction of alumina Al$_2$O$_3$ beyond this fraction the hardness trend started decreasing. In the hardness test, severe plastic flow has been concentrated in the localized region directly below the indentation, outside of which material still behaves elastically. Directly below the indentation the density of the particles increased locally, compared to regions away from the depression, the existence of very large hydrostatic pressure under the indentation can contribute to volumetric contraction of the metal matrix.
3.6 Fracture Toughness Results

Table 3 shows the fracture toughness of the samples. It is clear that there is improvement in 1 and 1.5 wt fractions. But for 1.5 sample, again, the voids caused a reduction in fracture toughness. Britteness behavior increased with increasing wt. fraction. Voids (flaws) contribute in increasing stress intensity factor that can directly affect the fracture toughness according to the law[13]:

\[ K_I = 1.14\sigma(\alpha)^{0.5} \]

where \( K_I \) is fracture toughness and \( \sigma \) is stress and \( \alpha \) is flaw radius.

Table 3 Impact test results for samples reinforce with 0.5wt%, 1wt% & 1.5wt% Al\(_2\)O\(_3\)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trial 1 (Nm)</th>
<th>Trial 2 (Nm)</th>
</tr>
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<tbody>
<tr>
<td>0.5%</td>
<td>7.4</td>
<td>7.7</td>
</tr>
<tr>
<td>1%</td>
<td>8.3</td>
<td>8.4</td>
</tr>
<tr>
<td>1.5%</td>
<td>6.9</td>
<td>6.7</td>
</tr>
</tbody>
</table>

3.7 Tensile Test Results

Table 4 represents results of the tensile tests. The specimens containing the alumina particulates exhibit higher yield and tensile strengths compared to the monolithic aluminum. In addition, similar to the micro-hardness behavior, the strengths of the composites first increase with the nanometric particulates content; however, when the content of the nanoparticulates exceeds 1.5wt.%, the strengths decrease.

Table 4 shows ultimate tensile stress and maximum elongation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ultimate tensile stress</th>
<th>Maximum elongation %</th>
</tr>
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<tbody>
<tr>
<td>0.5%</td>
<td>290 MPa</td>
<td>2.9</td>
</tr>
<tr>
<td>1%</td>
<td>255 MPa</td>
<td>2.1</td>
</tr>
<tr>
<td>1.5%</td>
<td>108 MPa</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The strength of the alloys corresponds to the particulate–dislocation interaction according to the Orowan bowing mechanism. After dislocations pass the particles, residual dislocation loops are left around each particle, increasing the material’s strength. If the particles are assumed to be equated, the strength. On the other hand, the difference in coefficient of thermal expansion between aluminum and Al\(_2\)O\(_3\) leadsto the generation of dislocations. The dislocation density generated is a function of reinforcement size, volume fraction, the product of the thermal mismatch, and the temperature change the strength can be estimated.

4. CONCLUSIONS

It is clear that the addition of ceramic nanoparticles to the Aluminum alloy generally enhances its properties. However, the main challenge is How to achieve regular or good distribution of particles across the matrix (The Aluminum alloy). The best results regarding enhancement of mechanical properties are wear resistance, fracture toughness and micro hardness but not tensile strength. Increasing stirring time can reduce agglomeration of added particles. Heat treatment refines grain size and consequently enhances mechanical properties. Increasing wt. % Increases mechanical properties for certain limit and drop down. Reducing capsule particle content and increasing its thickness lead to reduction in particles’ agglomerations.
REFERENCES