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The Effect of Process Parameters on the Mechanical Properties of A356 Al-Alloy/ZrO2 Nano-composite

Ahmed Y. Shash1,* , Amer E. Amer2, b, I. S. El-Mahallawi1, c and Moataz A. El-Saeed3, d

1 Cairo University, Mechanical Design and Production Department, Giza, Egypt
2 Beni- Suef University, Faculty of Engineering, Mechanical Design and Production Department, Beni Sueif, Egypt
3 Akhbar El-Youm Academy, Department of Mechanical Engineering, 6 of October City, Giza, Egypt

*ahmed.shash@cu.edu.eg, baeid958@yahoo.com, celmahallawi@bue.edu.eg, dmo3taz.elsaeed@gmail.com

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Abstract. In this study the effect of zirconia (ZrO2) nano-particles (40 nm) in reinforcing A356 aluminum alloys as a base metal matrix were investigated. Zirconia nano-powders were stirred in the A356 matrix with different fraction ratios ranging from (0, 1, 2, 3, 5%) by weight at variable stirring speeds ranging from (270, 800, 1500, 2150 r.p.m) at a mushy zone (600°C) and liquid state (700°C) using a constant stirring time for one minute. The microstructure revealed the change of grains from dendritic to spherical shape with increasing stirring speed. The Scanning Electron Microscopy of the fractured surface revealed the presence of nano-particles at the interdendritic spacing of the fracture surface and was confirmed with EDX analysis of these particles. The results of the study showed that the mechanical properties (strength, elongation and hardness) using ZrO2 as reinforcements were increased at the following parameters: 1500 r.p.m stirring speed in semi-solid state (600°C) and adding 3 wt.% of ZrO2.

Introduction

History is often marked by the materials and technology that reflect human capability and understanding. Many time scales begins with the stone age, which led to the Bronze, Iron, Steel, Aluminum and Alloy ages as improvements in refining and smelting took place and science made all these possible to move towards finding more advanced materials possible. Composite structures have shown universal savings of at least 20% over metal counterparts and a lower operational and maintenance cost [1]. As the data on the service life of composite structures is becoming available, it can be safely said that they are durable, maintain dimensional integrity, resist fatigue loading and are easily maintainable and repairable. Composites will continue to find new applications, but the large scale growth in the marketplace for these materials will require less costly processing methods and the prospect of recycling [2] will have to be solved [3-5].

Progress in the development of advanced composites from the days of E glass / Phenolic radome structures of the early 1940’s to the graphite/ polyimide composites used in the space shuttle orbiter are spectacular. The recognition of the potential weight savings that can be achieved by using the advanced composites, which in turn means reduced cost and greater efficiency, was responsible for this growth in the technology of reinforcements, matrices and fabrication of composites. If the first two decades of the last century saw improvements in the fabrication method, the systematic study of properties and fracture mechanics was at the focal point in the 60’s. Since that there has been an ever-increasing demand for newer, stronger, stiffer and yet lighter-weight materials in fields such as materials in the aerospace, transportation, automobile and construction sectors.

Composite materials are emerging chiefly in response to unprecedented demands from technology due to rapidly advancing activities in the aerospace and automotive industries. These materials have low specific gravity that makes their properties particularly superior in strength and modulus to many traditional engineering materials such as metals. As a result of intensive studies into the
fundamental nature of materials and the consequently developed better understanding of their structure property relationship, it has become possible to develop new composite materials with improved physical and mechanical properties. These new materials include high performance composites such as Polymer matrix composites, Ceramic matrix composites and Metal matrix composites etc. Continuous advancements have led to the use of composite materials in more and more diversified applications. The importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the market today more than 200 are composites [4-6].

For most applications, a homogeneous distribution of the particles is desirable in order to maximize the mechanical properties. In order to achieve a good homogeneous distribution of a particle in the matrix, the process parameters related with the stir casting method must be studied. Therefore it is essential to study the influence of the stirring speed and stirring time on the distribution of particles in MMC.

In the S. Balasivanandha Prabu [4-7] study, the stirring speeds have been taken as 500, 600 and 700 rpm and the stirring times taken were 5, 10 and 15 min. Many researchers have claimed enhanced properties for the produced composites relative to those produced by reinforcing with micro particles. Therefore, the aim of this work is to improve the mechanical properties of the A356 aluminum alloy using ZrO₂ ceramics nano particles by using both liquid metallurgy and semi-solid routes.

Experimental Work

Zirconia (ZrO₂) ceramic particles of 40 nm particle size were used as reinforcements to the A356 alloy with chemical composition illustrated in Table 1. A charge of 1 kg of A356 aluminium alloy was placed in the crucible of the crucible furnace and its temperature was raised to the required temperature (640°C). The addition of nanopowder was made while the metal was in liquid and semisolid states. When the addition was made in the liquid state the melt was brought to 700°C and the addition was made, then stirred and poured. When the addition was to be made in the semisolid state, the temperature of the melt was then brought down to 600°C. The nanopowder was added with a varied stirring speed of (270, 800, 1500, 2150 r.p.m.) and stirred mechanically using the apparatus illustrated in Figure 1. The stirring was carried out mechanically using a four blade impeller [8-11]. The ZrO₂ nanoparticles were preheated to 500°C, in order to avoid entering the sintering stage. After completion of stirring and mixing, the alloys were poured in preheated steel moulds at 300°C.

Table 1: Chemical Composition (in wt. %) of A356 cast Al-Si

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Chemical Composition (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>A356</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1: Apparatus used for preparing the MMNCs.
The tensile tests were conducted on round tension test specimens of diameter 5.02 mm and gage length 25.2 mm using a universal testing machine according to DIN 50125. The hardness tests were conducted on Rockwell hardness testing machine using a \( \frac{1}{16} \) diameter hardened steel ball and a 62.5 kg applied load. The microstructure examination was carried out using OLYMPUS DP12 optical metallurgical microscope equipped with a high resolution digital camera for investigating microstructure. The surface topography and fracture characteristics were studied using SEM to understand the fracture mechanism and also to detect the favorable sites for particle incorporation by using a JSM-5410 scanning electron microscope, with a high-resolution of 3.5 nm, and EDXS (energy dispersive X-ray spectrometer). PLINT TE 79 Multi Axis Tribometer Machine was used for measuring the friction force, the friction coefficient and the wear rate for the manufactured materials. In which a standard specimen with diameter of 8 mm and 20 mm length as a computerized Pin on Disc machine used for friction & wear testing of materials is loaded vertically downwards onto the horizontal disc. The wear tests were then performed for the A356 cast material with the following parameters: velocity = 0.8 m/s, time= 1200 s and load = 10 N. The differences in the weight of the samples were taken as an indication of the wear resistance of the material.

Results and Discussion

**Mechanical Properties of the NMMC Using ZrO\(_2\) Nanoparticles.** The mechanical properties (tensile strength, elongation% and hardness) of the produced castings with ZrO\(_2\) nanoparticles reinforcement are illustrated in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>ZrO(_2) wt%</th>
<th>Temperature (°C)</th>
<th>Stirring Speed(rpm)</th>
<th>UTS (MPa)</th>
<th>Elongation %</th>
<th>Hardness RB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>600</td>
<td>1500</td>
<td>155</td>
<td>5</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>600</td>
<td>1500</td>
<td>160</td>
<td>5</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>600</td>
<td>1500</td>
<td>167</td>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>600</td>
<td>1500</td>
<td>192</td>
<td>5</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>600</td>
<td>1500</td>
<td>164</td>
<td>6</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>600</td>
<td>270</td>
<td>159</td>
<td>5</td>
<td>69</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>600</td>
<td>800</td>
<td>165</td>
<td>5</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>600</td>
<td>2150</td>
<td>138</td>
<td>2.5</td>
<td>73</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>700</td>
<td>1500</td>
<td>110</td>
<td>2</td>
<td>76</td>
</tr>
</tbody>
</table>

Figure 2 shows the effect of wt.% fraction of ZrO\(_2\) nanoparticles on the UTS of the new composite using a 1500 r.p.m stirring speed in the semi-solid state (600°C). It can be seen that as a result of the nano-ZrO\(_2\) addition, the tensile strength and the hardness of the A356 aluminium alloy is enhanced. This is due to the higher hardness of the nano- ZrO\(_2\) particles. It also shows that nano-composites stirred at 1500 r.p.m, reinforced with 3 wt.% ZrO\(_2\) and cast from 600°C exhibit higher strength than those cast from the liquid state (700°C). The optimum stirring speed is shown to be at 1500 r.p.m.
The strength and hardness reduction by increasing the wt.% fraction addition of ZrO\textsubscript{2} nanoparticles beyond 3 wt.% has probably occurred due to the increase in porosity. Agglomerated particles and gas entrapment also can be considered as the main hardness reducing factors.

![Graph of UTS vs ZrO\textsubscript{2} Weight fraction](image1)

**Fig. 2:** The effect of wt.% fraction of ZrO\textsubscript{2} nanopowder on the UTS of MMC using 1500 r.p.m stirring speed at semi-solid state (600°C).

Figure 3 shows that as the stirring speed of the ZrO\textsubscript{2} nanoreinforced material increases to 1500 r.p.m., the UTS increases to reach 192 MPa. Beyond this stirring speed, the UTS decreases as the stirring speed increases possibly due to internal porosity and faster cooling of the slurry. The stirring speed has no visible effect on the ductility until reaching 850 r.p.m. At 2150 r.p.m stirring speed, the ductility reaches its minimum; this is possibly due to the high porosity content created in the casting, where its hardness at this stirring speed decreases after reaching its maximum value at 1500 r.p.m.

![Graph of UTS vs ZrO\textsubscript{2} Powder Stirring Speed](image2)

**Fig. 3:** The effect of stirring speed on the UTS of MMC with 3 wt.% fraction of ZrO\textsubscript{2} nano particles at semi-solid state (600°C).
The effect of 2 wt.% ZrO₂ fraction and the casting temperature on the ultimate tensile strength of nanocomposites is presented in Figure 4. It is clear that the UTS reaches the maximum value at a stirring temperature of 600°C. The tensile residual stress generated due to the difference in thermal expansion coefficients between the matrix alloy and the reinforcing phase is believed to enhance the tensile properties.

The improved strength and ductility exhibited by the nano-composites fabricated by the semi-solid method over that fabricated by the liquid metallurgy (700°C) method may be attributed to the high effective viscosity of the metal slurry that prevents particles from settling, floating, or agglomerating. This leads to a better distribution of the ceramic phase and hence produces better mechanical properties.

In the case of composites, the plastic flow of the matrix is constrained due to the presence of these rigid and very strong ZrO₂ particles. The matrix could flow only with the movement of ZrO₂ particles or over the particles during plastic deformation. While ZrO₂ content is significantly higher, the matrix gets constrained considerably due to the plastic deformation because of smaller inter-particle distances and thus results in higher degree of improvement in flow stress.

**Microstructural Evolution.** Figure 5 illustrates the microstructure of the A356 matrix alloy reinforced with 3 wt.% fraction of ZrO₂ at 600°C with 270 r.p.m. stirring speed. Figure 5 shows the presence of large grains of primary α-Al caused due to low stirring speeds which causes poor mechanical properties. When the stirring speed increases this causes more fine grains which leads to the improvement of the mechanical properties of the castings represented by microstructures.
Figure 5 shows the SEM of A356 alloy containing ZrO$_2$ agglomerated particles, in which the agglomeration could happen by the nano-particles reinforced inside the matrix during the melting stage which were not homogenously distributed inside the matrix and leading to a drop in the mechanical properties.

Wear Test Results. The average-wear results of A356 samples reinforced with 0, 1, 2, 3 and 5 weight% ZrO$_2$ nanoparticles are shown in Table 3. It can be seen from Table 3 that the addition of 1 weight% nanoparticles resulted in a significant drop in the friction coefficient, unaccompanied by any improvement in terms of weight loss. Increasing nanoparticles up to 5% resulted in a deterioration of wear resistance in terms of friction coefficient and weight loss, as also included from a previous research work [12].

Table 3: The average wear results of A356 samples reinforced with 0, 1, 2, 3 and 5 weight% ZrO$_2$ nanopowder.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Additions</th>
<th>Weight Loss (mg)</th>
<th>Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A356</td>
<td>3.7</td>
<td>0.39</td>
</tr>
<tr>
<td>2</td>
<td>A356 + 1% ZrO$_2$</td>
<td>4.1</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>A356 + 2% ZrO$_2$</td>
<td>4.2</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>A356 + 3% ZrO$_2$</td>
<td>4.9</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>A356 + 5% ZrO$_2$</td>
<td>5.3</td>
<td>0.43</td>
</tr>
</tbody>
</table>
The results show that the addition of 1 weight% nanoparticles did not produce a significant change in the wear resistance of the hypo-eutectic alloy A356, though there was a reduction in the friction coefficient. The fact that the wear resistance deteriorated after adding 2, 3 and 5 weight% nanoparticles (though the hardness and strength increased) may be attributed to microstructural effects as well as the high load used in the test [12].

Conclusion

- The nano-composites manufactured using the semi-solid route exhibited better mechanical properties when compared with those prepared by the liquid metallurgy rout.
- The addition of the preheated reinforced particles in the semi-solid state enhances the wettability of the reinforcement with the matrix compared to the wettability when reinforcement is made in the liquid state.
- The stirring speed has a significant effect on the mechanical properties of the nano-composites. Increasing the stirring speed over 1500 rpm causes a reduction in tensile strength due to the increase in micro-porosity. The alloy stirred with 1500 rpm exhibits the best tensile strength and elongation.
- The A356 matrix alloy reinforced with 3% weight fraction of ZrO₂ nano particles has the highest mechanical properties.
- Analysis using both scanning electron microscopy (SEM) at high magnifications shows evidence for the possibility of incorporating and entrapping nano-sized particles within the interdendritic interface developing during the solidification of the dispersed alloys. However, the role of nano-particles on the microstructural and mechanical characteristics of the MMNCs still needs further investigation.
- The introduction of varying amounts of nanosized particles to the A356 alloy did not produce a significant change on the wear resistance of the tested hypo-eutectic alloy A356 material with 1% nanoparticles and resulted deterioration after adding 2%, 3% and 5% nanoparticles, though a drop in the friction coefficient occurred at 1% addition.

References


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