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Fabrication and Studying the Mechanical Properties of A356 Alloy Reinforced with Al_2O_3-10% Vol. ZrO_2 Nanoparticles through Stir Casting

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Abstract

Al_2O_3-ZrO_2 with a high level of hardness and toughness is known as ceramic steel. Due to its unique properties it can be used as a reinforcement in fabrication of metal matrix composites. In this study, nanoparticles of Al_2O_3-10% ZrO_2 with an average size of 80 nm were used to fabricate Al matrix composites containing 0.5, 1, 1.5 and 2 wt.% of the reinforcement. The fabrication route was stir casting at 850˚C. There is no report about usage of this reinforcement in fabrication of composites in the literature. The microstructures of the as-cast composites were studied by scanning electron microscope (SEM). Density measurement, hardness and tensile properties were carried out to identify the mechanical properties of the composites. The results revealed that with increasing the reinforcement content, density decreased while yield, ultimate tensile strength and compressive strength increased. Also, hardness increased by increasing the reinforcement content up to 1 wt.% Al_2O_3-10% ZrO_2 but it decreased in the samples containing higher amounts of reinforcement.

Keywords: Stir Casting, Al Matrix Composite, Al_2O_3-10% ZrO_2 Nanoparticles

1. Introduction

Composites containing discontinuous reinforcements especially particulate metal matrix composites have found commercial applications [1-3] because they can be fabricated economically by conventional techniques. Al-alloy based composites have attracted attentions due to their processing flexibility, low density, high wear resistance, heat treatment capability and improved elastic modulus and strength [4]. AMCs are fabricated by incorporating ceramic particles like SiC, B_4C, and Al_2O_3 with particle size of micron or nano-scale into Al-alloy matrix [5].

Ultra fine particles such as nanoparticles noticeably reduce interparticle spacing resulting in increased mechanical properties. On the other hand, nanoparticles have a high tendency to form agglomerates. Thus, for each technique and matrix, it is important to find out the optimum size, reinforcement content and parameters of fabrication to minimize agglomeration [6].

Factors such as different particle sizes, density, geometries, flow or the development of an electrical charge during mixing may lead to agglomeration [7]. In this process, mixing of matrix and reinforcement is a critical step to obtain a homogenous distribution of reinforcing particles in matrix. Since by reducing ceramic particle size the stress concentration level on each particle is decreased and makes it difficult to be fractured, nanoscale ceramic particles have attracted attentions in academia and industry [8,9].

Generally, wettability of the reinforcement ceramic particles by a liquid metal is very poor. Good wetting between ceramic particles and liquid metals leads to a proper bonding between these two during and after casting.Various techniques like pretreatment of particles [11], adding elements such as magnesium and lithium into the matrix as surface active agents [12,13], coating or oxidizing the ceramic particles [14,15], cleaning the particle surface by ultrasonication and different etching methods [16,17] have been tried to improve wettability. Among various techniques to fabricate metal matrix composites reinforced with ceramic particles, stir casting is one of acceptable routes for commercial production. However, this method needs delicate optimization of parameters like casting temperature, stirring velocity, reinforcement content, etc. [18,19]. In this research, four composites with different Al_2O_3-10% ZrO_2 content as reinforcement were fabricated via stir casting. Al_2O_3-10% ZrO_2 nanoparticles were wrapped in aluminum foil to facilitate addition to the molten aluminum alloy. The casting temperature was fixed at 850˚C and simultaneous stirring of molten aluminum at constant stirring velocity was carried out. Then specific tests were carried out to identify the effect of reinforcement content on the mechanical properties of the as-cast composites.

2. Experimental

Aluminum alloy (A 356) was used the matrix and nano-sized Al_2O_3-10% ZrO_2 was employed as the reinforcement in fabrication of samples. Chemical composition of A356 is presented in **Table 1**.

The samples were prepared using a resistance furnace, equipped with a stirring system. After smelting of aluminum ingots, 3 g Keryolit was added to the molten metal and stirring was carried out at constant rate of 420 rpm for 14 min. The stirring rate was adapted, according to the results of literature and previous works [19,20]. Al_2O_3-10% ZrO_2 nanoparticles were wrapped in aluminum foils thence added to the molten metal during stirring. The casting was performed at 850˚C. Steel mold was used for casting of specimens. Finally, the as-cast composites were prepared for subsequent microstructural and mechanical analyses. Bulk density measurement was carried by Archimedes method. Theoretical density was calculated by using simple rule of mixtures. Porosity of the composites was estimated using the following relation:

$$\text{Porosity} = 1 - \left\{ \rho_{mc} \Big/ \left(\rho_m \left(1 - V_p\right) + \rho_p V_p \right) \right\}$$

where ρ_{mc} is the measured density of the composites, ρ_m is the theoretical density of the matrix alloy and V is the volume fraction of Al_2O_3-10% ZrO_2. It should be metioned that the weight percentages of the reinforcement were converted to volume percentage to be used in the above relation. Microstructural studies of the as-cast samples were carried out by scanning electron microscope (SEM-Philips XL 30). The tension tests were carried out in air at room temperature (Instron Universal Testing Machine-1195 machine).

Also, the compressive strength test was conducted in air at room temperature (Zwick testing machine). At least 3 specimens were used for each composite sample. Brinell method was used to measure the hardness of the samples after grinding and polishing them down to 1 µm. At least 5 indentations on two polished specimens were done to obtain data of hardness.

3. Results and Discussion

3.1. Microstructural Studies of As-Cast Composites

The microstructural examination of the as-cast composites generally revealed that Al_2O_3-10%ZrO_2 nanoparticles were not distributed uniformly in the matrix and regional clusters of particles exist (see **Figure 1**). Since the wettability of particles by molten matrix is poor a uniform distribution of particles cannot be observed in the composites. In addition, other factors like stirring speed, pouring conditions, solidification rate, etc. have

Table 1. Chemical composition of A356 alloy.

Element	Si	Mn	Fe	Ni	Ti	Zn	Sr	Mg	Al
Wt.%	7.22	0.01	0.15	0.016	0.13	0.04	0.01	0.45	balance

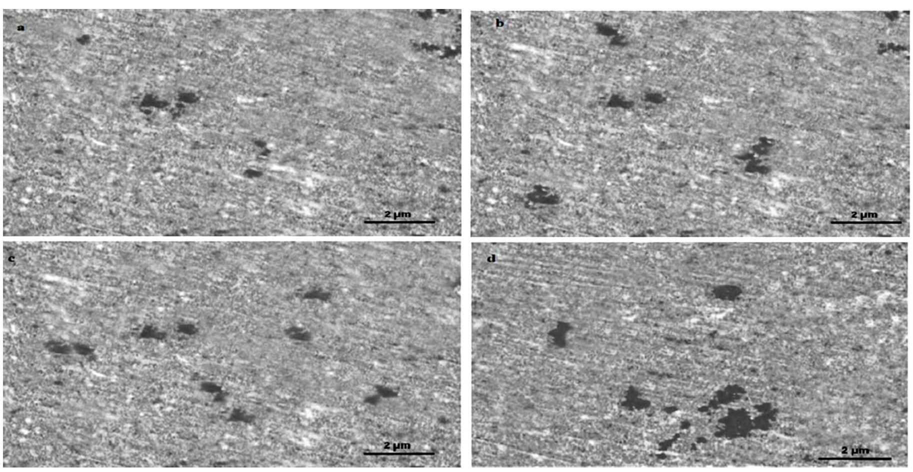


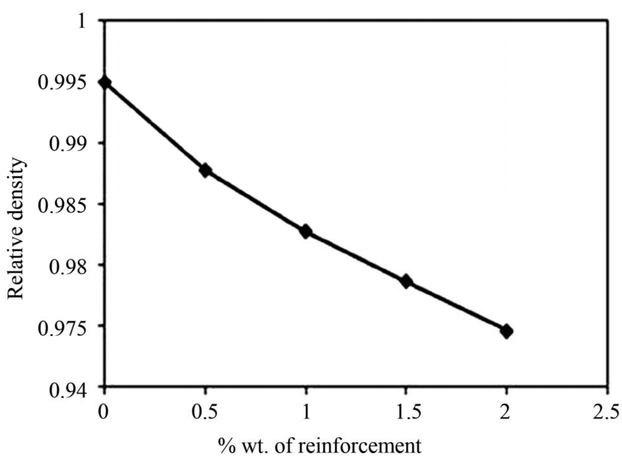
Figure 1. SEM images of as-cast Al- Al_2O_3-10% ZrO_2 composites containing (a) 0.5 wt.%, (b) 1 wt.%, (c) 1.5 wt.%, (d) 2 wt.% Al_2O_3-10% ZrO_2 nanoparticles.

noticeable influence on the distribution of particles [20].

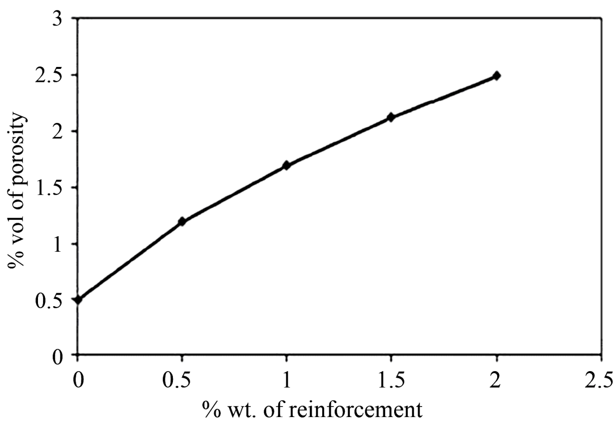
3.2. Density and Porosity Measurements

The measured densities of the as-cast composites vs. reinforcing nanoparticles content are shown in **Figure 2(a)**. It is clear that by increasing the reinforcement content, density decreased.

The high amount of porosity in the samples can be ascribed to air bubbles entering the melt either independently or as an air envelope to the reinforcing particles [17]. The results of the measured densities demonstrate that by increasing reinforcing nanoparticles content, density decreased because of higher possibility of agglomeration at higher percentages of nanoparticles. Agglomeration, in turn, leads to porosity formation. In short, by increasing nanoscaled reinforcements, porosity content increased. This result is confirmed by porosity content vs. amount of Al_2O_3-10% ZrO_2 nanoparticles in **Figure 2(b)**.



(a)



(b)

Figure 2. (a) Relative density samples vs. weigh percent of reinforcement. (b) Volume percent of porosity in samples vs. weigh percent of reinforcement.

3.3. Tensile Behavior

The results of tensile tests for the samples are presented in **Figure 3(a)**. it is clear that by increasing Al_2O_3-10% ZrO_2 nanoparticle content, yield and ultimate tensile strength (UTS) increased.

Beneficial effect of Al_2O_3-10% ZrO_2 addition on the strength could be explained by the reduction of mean free path by increasing Al_2O_3-10% ZrO_2 volume fraction, and also with the increased density of dislocations generated as a result of the difference in thermal expansion coefficients of the matrix and reinforcement [21]. Thermal expansion coefficients of A356, Al_2O_3 and ZrO_2 are about 23.5×10^{-6}, 8.1×10^{-6} and 10.3×10^{-6} 1/°C, respectively. Also, low level of ductility in the as-cast state may be ascribed to the high porosity content, early void formation at low strains during tensile elongation and heterogeneous particle distribution. Therefore, ductility is expected to decrease by increasing reinforcement content [22].

3.4. Compressive Behavior

The result of compressive tests is shown in **Figure 3(b)**. It can be understood from these results that by increasing the Al_2O_3-10% ZrO_2 content, the compressive strength increased continuously. Although the porosity content of the samples increased by increasing Al_2O_3-10% ZrO_2 content (See **Figure 2(b)**), compressive strength increased. This demonstrates that porosity content has no disadvantageous effect on compressive strength and the content of reinforcement plays the major role *i.e*. the compressive strength increased by increasing Al_2O_3-10% ZrO_2 content.

The plastic flow of matrix is constrained due to the presence of these rigid and very strong Al_2O_3-10% ZrO_2 nanoparticles.

The matrix could flow only with the movement of Al_2O_3-10% ZrO_2 particle or over the particles during plastic deformation. While Al_2O_3-10% ZrO_2 content is significantly higher, the matrix gets constrained considerably to the plastic deformation because of smaller inter-particle distance and thus results in higher degree of improvement in flow stress. It has been understood that the plastic flow of the composite is due to the plastic flow of the matrix [23]. The strain hardening of the composite is primarily due to hardening of the matrix during its plastic flow. The strain hardening of matrix is expected to be influenced by the following factors: (i) dislocation density and dislocation to dislocation interaction, (ii) constraint of plastic flow due to resistance offered by Al_2O_3-10% ZrO_2 nanoparticles [6].

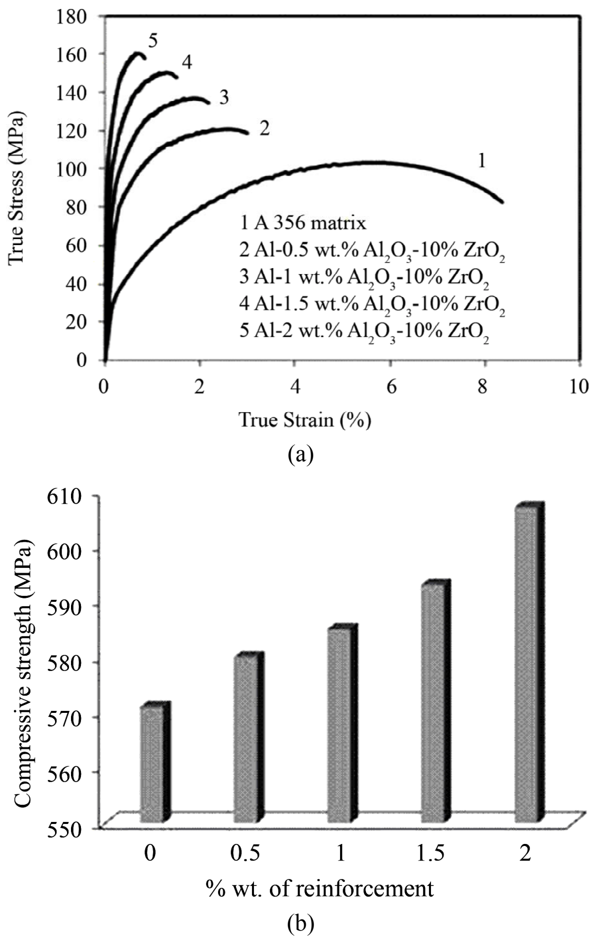


Figure 3. (a) True stress vs. true strain curves for fabricated composites. (b) The compressive strengths of fabricated composites vs. reinforcement content.

3.5. Hardness Measurements

The hardness of the samples vs. Al_2O_3-10% ZrO_2 content is presented in **Figure 4**. It is clear that the hardness of a 1 1

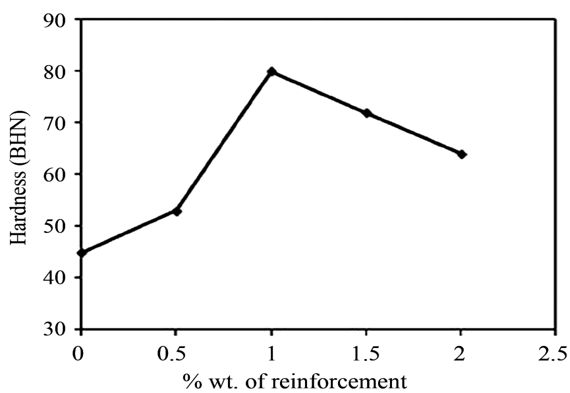


Figure 4. Measuerd values of hardness (BHN) vs. weight percentage of Al_2O_3-10% ZrO_2 for fabricated composites.

composites as shown by figure 4 was higher than that of the matrix. This is because of the presence of hard Al_2O_3-10% ZrO_2 nanoparticles. By increasing the reinforcement content up to 1 wt.% Al_2O_3-10% ZrO_2 the hardness increased but the hardness of the sample containing 1.5 and 2 wt.% of Al_2O_3-10% ZrO_2 decreased. This is because of heterogeneous distribution of nanoparticles and high porosity content. It should be noted that these results are the average number of at least 5 indentations, thus some indentations were carried out in the regions containing no or low contents of reinforcing particles or containing high porosity amounts.

4. Conclusions

Al-alloy based composites reinforced with Al_2O_3-10% ZrO_2 nanoparticles were fabricated by stir casting at 850˚C. Microstructural and mechanical behaviors were studied. It was concluded that by increasing the reinforcement content, density decreased while yield, ultimate tensile strength and compressive strength increased. Ductilities of the composites were low because of high porosity content, early void formation at low strains during tensile elongation and heterogeneous particle distribution. Also, by increasing the reinforcement content up to 1 wt.% Al_2O_3-10% ZrO_2 hardness increased but the hardness of the sample containing 1.5 and 2 wt.% Al_2O_3-10% ZrO_2 decreased.

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