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Investigation on mechanical properties and fracture behavior of A356 aluminum alloy based ZrO_2 particle reinforced metal-matrix composites

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Abstract

In the present study, an investigation has been carried out on the influences of ZrO_2 content and casting temperature on mechanical properties and fracture behavior of A356 Al/ZrO_2 composites. A356 aluminum alloy matrix composites reinforced with 5, 10 and 15 vol% ZrO_2 were fabricated at various casting temperatures, viz. 750, 850 and 950 °C via the stir casting method. Based on the obtained results, optimum amount of reinforcement and casting temperature were determined by evaluating the density and mechanical properties of the composites. Hardness and tensile tests were carried out in order to identify the mechanical properties of the composites. Fracture surfaces of the samples were also studied to identify the main fracture mechanism(s) of the composites. The results indicate that all samples fractured due to the inter-dendritic cracking of the matrix alloy. Reinforcing the Al matrix alloy with ZrO_2 particles, improved the hardness and ultimate tensile strength of the alloy to the maximum values of 70 BHN and 232 MPa, respectively. Consequently, the highest mechanical properties were obtained by the specimen including 15% of ZrO_2 produced at 750 °C.

Keywords: B. Composites; C. Fracture; C. Mechanical properties; D. ZrO_2

1. Introduction

Metal matrix composites (MMCs) represent a new generation of engineering materials due to their special mechanical and physical properties in which a strong ceramic reinforcement is incorporated into a metal matrix to improve its properties including specific strength, specific stiffness, wear resistance, excellent corrosion resistance and high elastic modulus [1–3]. MMCs combine metallic properties of matrix alloys (ductility and toughness) with ceramic properties of reinforcements (high strength and high modulus), leading to greater strength in shear and compression and higher service-temperature capabilities. Therefore, MMCs tend to replace conventional materials in various fields of application such as automotive, aeronautical, aerospace, mechanical engineering, as well as in other industries because of its own properties [1].

Particle reinforced aluminum matrix composites can be fabricated by using conventional material manufacturing methods with improved mechanical and physical properties. These properties include improved strength, high elastic modulus, creep strength, fatigue strength, hardness and wear resistance, corrosion resistance and low thermal expansion. Among the manufacturing processes for aluminum matrix composites, the stir-casting technique has been developed to manufacture a wide range of these materials due to its low cost, simplicity and high production rate [4]. However, the improper control of some process parameters in this technique commonly produces the composites with defects such as porosity, weak bonding between reinforcement and matrix, non-uniform distribution of the particles, large reinforcement free zones, which may result in decreasing mechanical properties [5–7].

Although a great deal of work has been conducted on the aluminum matrix composites, there is limited information over the effect of manufacturing variations on fracture behavior of these materials.

As the ceramic reinforced aluminum matrix composites have important applications in many fields of the industry, In the present study, Al–ZrO_2 composites were fabricated

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by the stir casting method with different volume percents of ZrO_2 content (as the reinforcement phase), and casting temperatures. Subsequently, the effects of these two parameters on mechanical properties (tensile and hardness tests) were studied. Also, fractography was carried out on the samples to evaluate the fracture behavior of the aforementioned composites.

2. Materials and methods

In this study, A356 aluminum alloy was used as the matrix material while Yttria stabilized zirconia powder (ZrO_2–3 mol% Y_2O_3, $D_{50}=0.79$ μm) was used as the reinforcement and the composites were produced using a vortex method. In order to manufacture the composites, the aluminum alloy was melted at 750 °C, 850 °C and 950 °C, using a furnace and an impeller which was made of graphite. The melt was stirred at a constant speed of 300 rpm for 13 min and the different amount of zirconia particles (5, 10, and 15 vol%) were added into the molten alloy. Stirring was carried out for 2 more minutes and the molten composites were poured inside a metallic mold (cylindrical shape with 15 cm height and 15 mm diameter).

To investigate the density of the fabricated specimens, a density test system was used to measure density according to the Archimedes method. After grinding and polishing the specimens, the hardness tests were carried out with a load of 306.56 N to determine the hardness values of the mentioned samples. Samples were tested in an ESEWAY DV RB-M testing unit with the HB (Brinell test) method. At least five indentations were made for each hardness measurement and the average hardness values are reported.

Cylindrical samples of height 150 mm and diameter 15 mm were machined using an EDM device from the composite specimens. In order to measure tensile strength of the samples, tensile tests were conducted at room temperature according to ASTM.B557 [8], using an INSTRON 1195 test unit. Also, scanning electron microscope (SEM, Camscan-MV2300) was employed to study the fracture surface of the fractured samples.

3. Results and discussion

3.1. Density measurements

Fig. 1 shows the experimental densities of the composites versus the volume fraction of ZrO_2 particles. It can be seen that the density increases with the ZrO_2 content at 750 °C. This behavior is consistent with the mixture rule in which the total density increases with the volume percent of the second phase [9]. For the composites, cast at 850 °C, increasing the volume content of zirconia led to increase in the density up to 10%. Then, density followed a decreasing trend which is due to the effects of high temperature and agglomeration at high content of reinforcement. Moreover, tensile stresses originated from thermal expansion coefficient mismatch between metal matrix and rigid reinforcement (CTE of aluminum and zirconia are $24\times10^{-6}\,K^{-1}$ and $10\times10^{-6}\,K^{-1}$ respectively), would normally form defects such as porosity and dislocations around the particles [10].

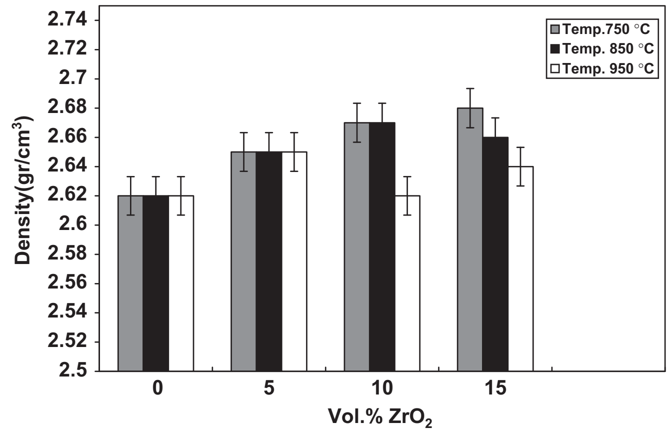

Fig. 1. The density results of the Al alloy and the composite specimens containing 5, 10 and 15 vol% ZrO_2 fabricated at 750, 850 and 950 °C.

As seen in this figure, increasing the temperature to 950 °C increased the density of composite up to 5 vol% ZrO_2. It seems that at this condition, temperature plays an important role to increase the wettability of particles. However, there is a minimum value of 10 vol% ZrO_2, which may be attributed to air entrapment due to high fluidity and turbulence of the melt at high temperature. In general, the density of the composite is determined at this temperature by two important factors: high temperature and volume content of the second phase. In contrast, in the composite with 15 vol% of zirconia, the density is increased, since the effect of second phase content is more significant than the effect of temperature.

3.2. Hardness test

The hardness variation of samples with the ZrO_2 (vol%) is illustrated in Fig. 2. The hardness of all composites is higher than the A356 aluminum alloy one (45 HB), due to the presence of ZrO_2 particles. Also, it can be attributed to the higher hardness of zirconia particles compared to aluminum alloy. In fact, the hardness of composite depends on the hardness of the reinforcement and the matrix. Hardness properties of the composite fabricated at 750 °C were improved by increasing the amount of ZrO_2 particles in accordance with the density variation at this temperature. As mentioned before, the coefficient of thermal expansion (CTE) of ceramic particles is less than that of aluminum alloy. So, an enormous amount of dislocations are generated at the particle–matrix interface during solidification process, which further increases the matrix hardness. The higher the amount of particle–matrix interface, the more is the hardening due to dislocations [11].

The hardness was enhanced with the content of ZrO_2 up to 5 vol% at 850 °C and remained constant by increasing the amount of ZrO_2 up to 10 vol%. However, the hardness

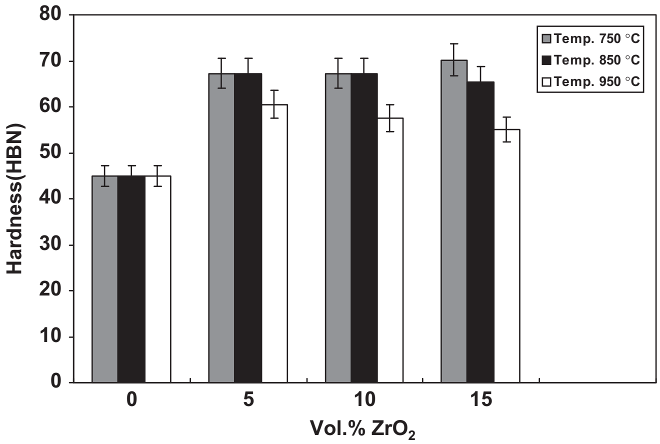

Fig. 2. The hardness results of the Al alloy and the composite specimens containing 5, 10 and 15 vol% ZrO_2 fabricated at 750, 850 and 950 °C.

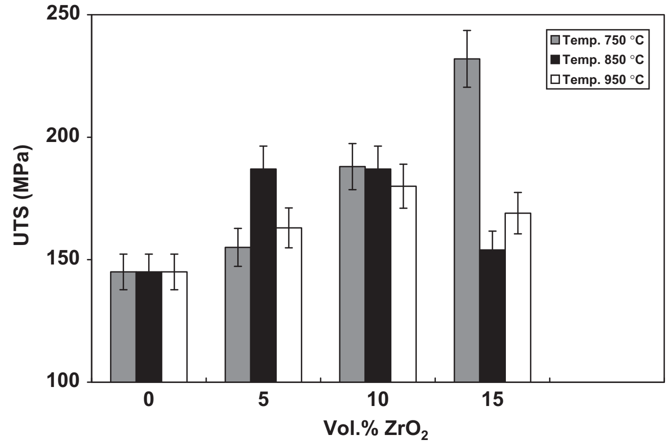

Fig. 3. The UTS results of the Al alloy and the composite specimens containing 5, 10 and 15 vol% ZrO_2 fabricated at 750, 850 and 950 °C.

values were reduced as the amount of ZrO_2 was increased over 10 vol%. This behavior can be attributed to the effect of reinforcement content as a factor which raises the hardness and volume content of voids. Therefore, in the range of 0–5 vol%, the reinforcement content is the dominate factor, while in the range over 10 vol% the main factor which controls the hardness variations is voids content. Moreover, the constant values of hardness between 5 and 10 vol% of ZrO_2 can be due to the opposite effects of reinforcements and voids which neutralize each other. Furthermore, by increasing the temperature to 950 °C, the hardness values are lower than the ones at 750 °C and 850 °C which may be due to the defect formation as a result of high fluidity of the melt at high temperature.

3.3. Tensile test

The effect of ZrO_2 content on ultimate tensile strength (UTS) of the samples, for each casting temperature is depicted in Fig. 3. In brief, the strengthening is a result of two major contributions, indirect strengthening and direct strengthening [12]. The tensile strength shows an improvement with increasing the content of ZrO_2 at 750 °C which could be the result of increasing dislocations density and their pile-ups behind the uniform distributed ZrO_2 particles [10]. In other words, increasing ZrO_2 volume percent resulted in an increase in ultimate tensile strength. Indirect strengthening results from the changes in the matrix microstructure that takes place due to the presence of reinforcement particles. In the Al–ZrO_2 composites, indirect strengthening arises from an increase in dislocation density due to the coefficient of thermal expansion mismatch between ZrO_2 and Al alloy (as demonstrated, CTE plays an essential role in density, hardness and tensile tests). The density of these thermally induced dislocations also increases with increasing volume fraction of ZrO_2, so the indirect strengthening contribution increases with increasing ZrO_2 content [12,13].

On the other hand, this gradual enhancement seems to be due to work-hardening behavior.

Aluminum matrix can deform plastically. But, the deformation of reinforcing particles generally remains elastic due to the much higher yield stress. So the stress concentration within the particles would be very high. In the process of load transfer, the matrix transfers the load to the ZrO_2 particles. So if the boundary is assumed to be strong, ceramic particles prevent plastic deformation of the matrix and this leads to the direct strengthening contribution and higher work-hardening rate [12,14].

Also, for the composites cast at 850 °C and 950 °C, the maximum tensile strength was achieved by the ones containing 5–10 vol% ZrO_2. However, the composites containing 15 vol% ZrO_2, showed the decreasing trend of tensile strength which is mainly due to the formation of porosities as a result of high ZrO_2 content and also air entrapment during high temperature casting. According to Figs. 1 and 3, among composites with the different amounts of ZrO_2 cast at various temperatures, the one which has maximum density shows the highest strength (15 vol% ZrO_2, 750 °C). Therefore, it can be concluded that composite with 15 vol% ZrO_2 content, cast at 750 °C, represent maximum tensile strength and can be considered as the optimum fabrication conditions.

3.4. Fracture behavior and fractographic observation

In general, the fracture modes of MMCs can be controlled by a number of material and processing parameters such as the type, shape, volume fraction and distribution of the particles, as well as the matrix and interface properties which may include the solute segregation, precipitation effect, porosity amount, interfacial bonding strength, original sample surface roughness, etc. Most of these parameters will be strongly influenced by the processing and thermal treatment history. Failure in particulate-reinforced MMCs is believed to be due to three different sources, namely, the matrix/reinforcement interfacial decohesion, reinforcement fracture, and failure in the matrix [15–21]. To determine the fracture mechanism(s) in samples with minimum and maximum volume fraction of reinforcement particles, microscopic observations were made on the fractured samples containing 5 and 15 vol% of ZrO_2. Figs. 4–6 show the SEM fracture surfaces after tensile testing for the composites poured at 750 °C, 850 °C and 950 °C, respectively.

Fracture surface observations of the samples show that the main controlling fracture mechanism is inter-dendritic cracking. This failure mode is identical for the A356 unreinforced alloy which has been recently investigated [22]. During

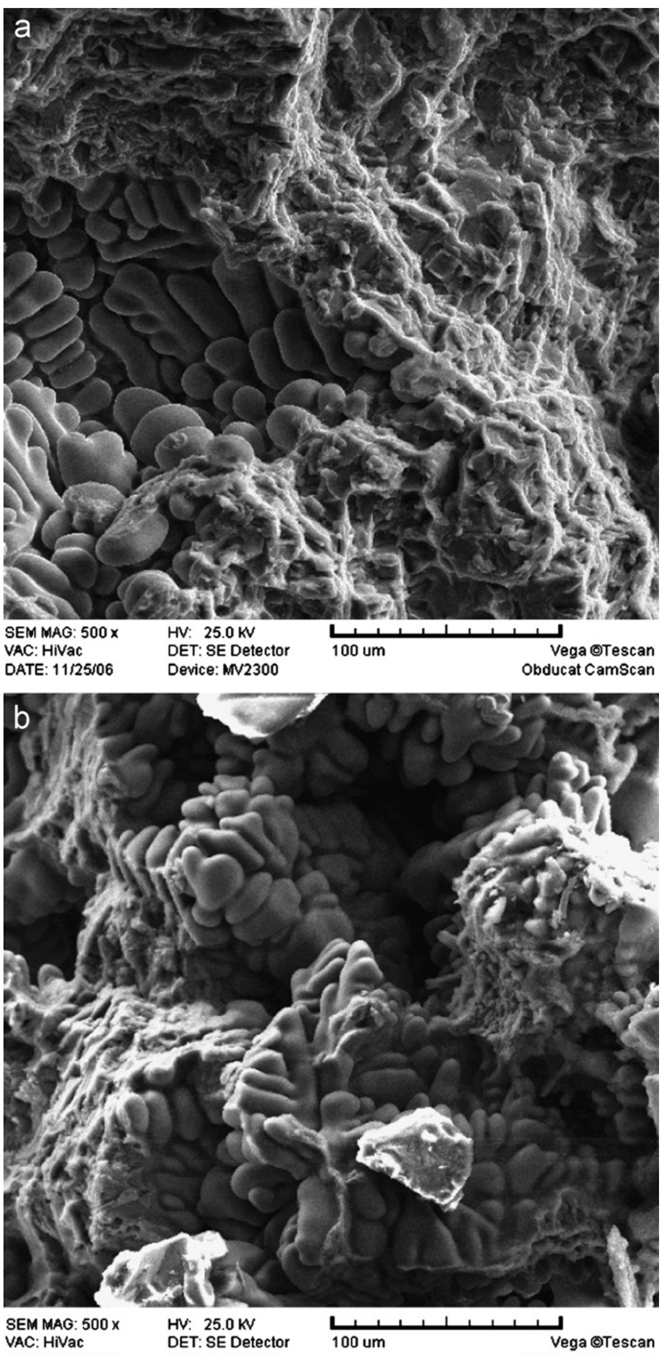

Fig. 4. SEM micrograph of fracture surfaces of composites fabricated at 750 °C containing (a) 5 and (b) 15 vol% ZrO_2.

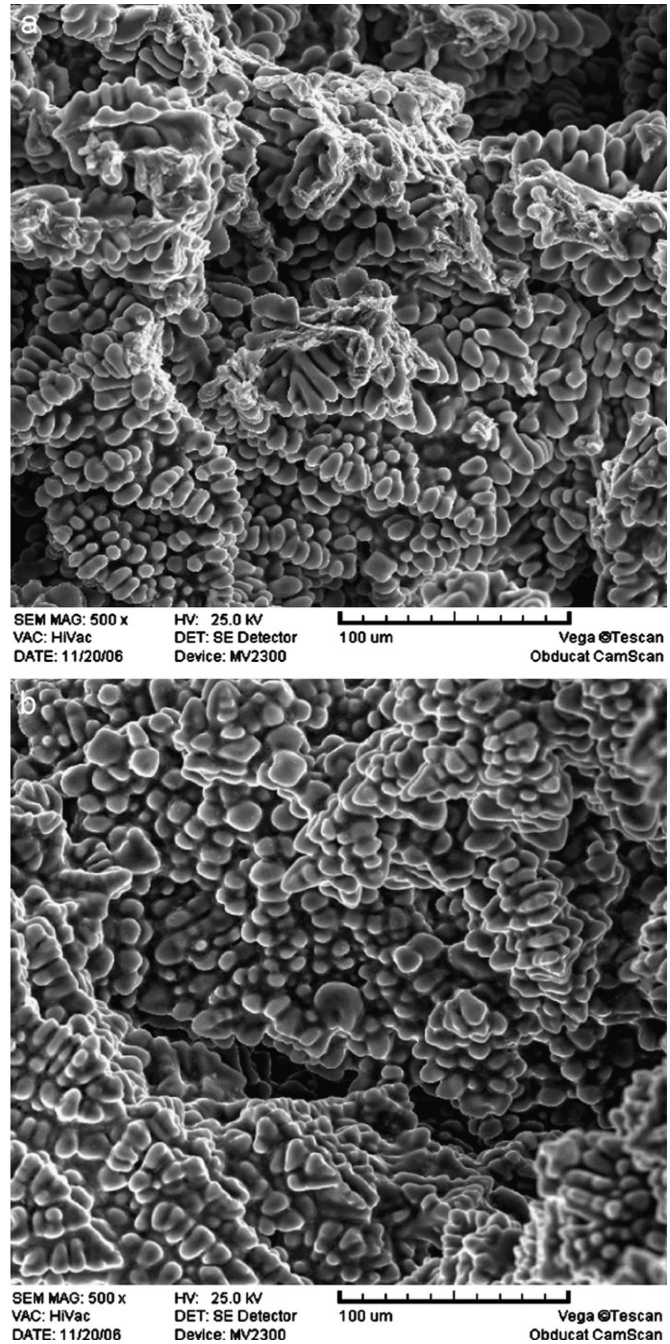

Fig. 5. SEM micrograph of fracture surfaces of composites fabricated at 850 °C containing (a) 5 and (b) 15 vol% ZrO_2.

solidification of the composite, the ZrO_2 particles and alloys elements (mainly Si), are rejected to the solid/liquid interface and segregate to the inter-dendritic regions [10,15]. The micro-cracks propagate along inter-dendritic aluminum-silicon eutectic and silicon particles resulted in failure of the specimen which implies that the fracture of this composite is dominated by failure of the matrix alloy.

However, some areas of the composites fracture surfaces consist of dimples which may be a result of the void nucleation and subsequent coalescence by strong shear deformation and fracture process on the shear plane [23].

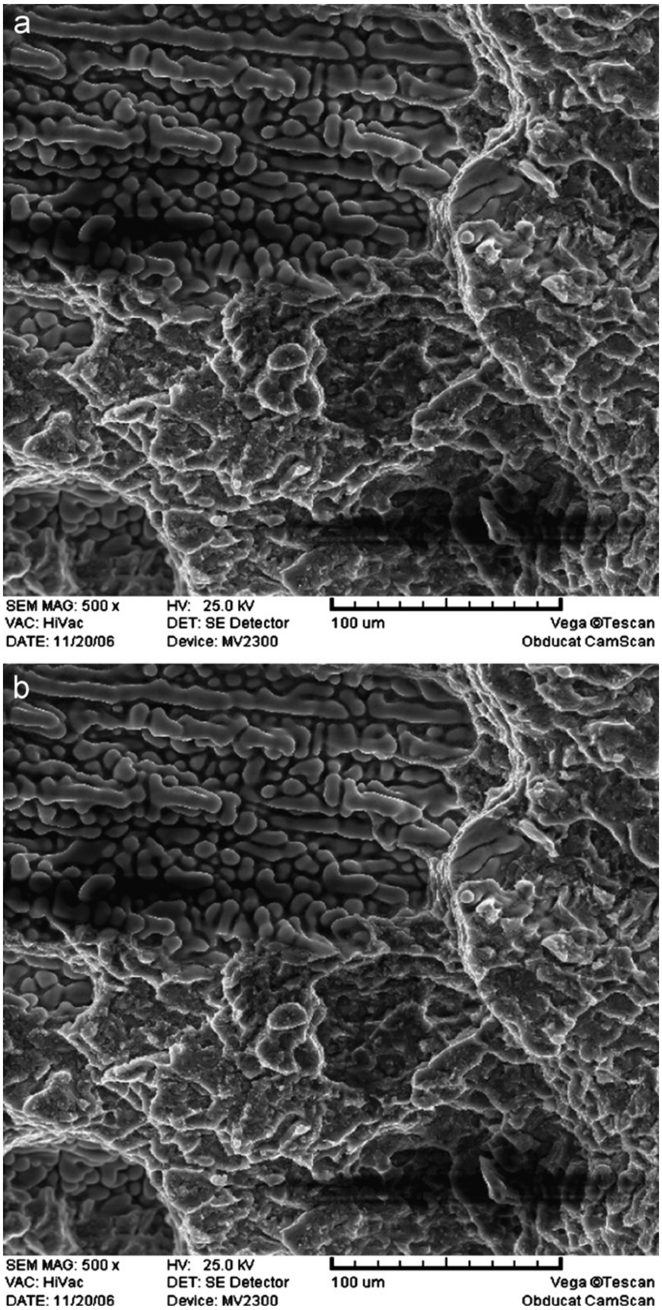

Fig. 6. SEM micrograph of fracture surfaces of composites fabricated at 950 °C containing (a) 5 and (b) 15 vol% ZrO_2.

The dimpled rupture occurs mostly by voids initiation at eutectic silicon particles [22].

4. Summary and conclusions

Results presented in this investigation reveal the effect of the reinforcement content and the casting temperatures on mechanical properties and fracture behavior of Al–ZrO_2 composites which were fabricated by the stir casting method.

Mechanical properties such as hardness and ultimate tensile strength were improved, comparing with the unreinforced alloy. Composite containing 15 vol% ZrO_2 fabricated at 750 °C showed the maximum value of the hardness and ultimate tensile strength in comparison with other specimens which could be attributed to the presence of ZrO_2 particles, dislocations density increasing and their pile-ups behind the uniform distributed ZrO_2 particles. Thus, it can be concluded that the optimum fabrication conditions of the composite processing was provided with 15 vol% ZrO_2 and casting at 750 °C.

Fracture surface observations of the samples shows that the failure of the A356/ZrO_2 composite is similar to the unreinforced A356 alloy one which was controlled by inter-dendritic cracking of the matrix. In addition, a number of dimples were observed on the fractured surfaces of all samples which could be a result of the void nucleation and subsequent coalescence during the fracture process.

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