THE EFFECT OF COMPOSITION AND STIR-CASTING PARAMETERS ON THE MECHANICAL PROPERTIES OF Al/ZrO_{2P} NANOCOMPOSITES

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ABSTRACT

Aluminum based composites reinforced with ceramic particles, have been used to substitute steel. ZrO_2 nanoparticles were found to be a promising candidate for a vast material application due to its high hardness, high modulus of elasticity and excellent thermal stability. In this study, aluminum (A356.1) and ZrO_2 nanoparticles were selected as raw materials. Samples of composites were made at different percentage of ZrO_2 (1.5, 2.5, and 5vol %). The casting temperatures were selected 800, 850, and 950°C. Microstructure of composite specimens was examined using SEM and EDS. Mechanical properties such as compressive yield strength, toughness and hardness were determined. The experimental results show that the mechanical properties like compressive yield strength and hardness markedly improved by adding ZrO_2 nanoparticles. The maximum values were for samples containing 2.5vol% of nanoparticles casted at 850°C.

KEYWORDS: ZrO_2, aluminum, nanocomposite, hardness, compressive yield strength.

1. INTRODUCTION

In last years, the development of metal matrix composites (MMCs) is observed in many industrial branches among others in the aircraft industry, automotive and armaments ones as well as in electrical engineering and electronics, etc. [1-3]. The strengthening mechanism for MMCs with fine particles has been theoretically studied [4, 5]. Considerable attention is focused on Al metal matrix composites (Al-MMCs) because of their superior properties such as low coefficient of expansions and high specific strengths in comparison with most of conventional materials. Al based composites reinforced with particles, whiskers and ceramic fibers have been used to substitute steel [6]. Particle reinforced composites exhibit an excellent heat and wear resistance due to their superior hardness and heat resistance characteristics of the particles distributed in matrix [7].

It is believed that the properties of metal matrix composites embedded with nano-sized ceramic particles (less than 100 nm) would be enhanced considerably even with a very low volume fraction of these nanoparticles. The potential advantages of these metal matrix nanocomposites (MMNCs) have generated excitement in both academia and industry. The need for cast structural components of high performance aluminum alloy composites is expected to increase, as automotive industries are forced to improve the fuel efficiency of their products.

Various fabrication methods, such as mechanical stir casting [8-15], powder metallurgy [16, 17], and squeeze casting [18-21] have been applied to produce discontinuously micro particles reinforced Al-MMCs. Among these methods, stir casting is an easily adaptable and cost-effective method. This technique is also capable of the near-net-shape formation of the composites into complex shapes by conventional foundry processes. It is attractive because of simplicity, flexibility and most economical for large sized components to be fabricated [22].

In this paper, Al356/ZrO_2 nanocomposites were fabricated by stir casting route. The microstructure of produced nanocomposites has been investigated by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX). The effect of nano-sized ZrO_2 particles addition on the mechanical properties of aluminum matrix composite was studied by uniaxial compression and Brinell hardness tests.

2. EXPERIMENTAL PROCEDURE

A356.1 alloy with the composition shown in table 1 was used as the matrix alloy. ZrO_2 powder with the mean size of 125 nm was also used as reinforcement phase. The ZrO_2 powder was ball milled in isopropyl alcohol for 12 hr using high purity Al_2O_3 balls to obtain nano-sized powder. The mixture was then dried in a rotary vacuum evaporator. These samples were passed through a 60 mesh sieve. Aluminum powder with the size of 16 μm was mixed with ZrO_2 powder and compacted into the aluminum foils. Composites were prepared by dispersing 1.5%, 2.5% and 5% volume fractions of ZrO_2 particles in the molten aluminum. The melt was stirred with a graphite stirrer at a constant rotation speed of 400 rpm. About 4gr cryolite was plunged into the melt to improve the foundry condition and prevent from slag formation. Stirring was continued for a few minutes. The melt was then casted at 800, 850, and 950 ^{o}C inside a metallic mold. This kind of mold was used to prevent unwanted conditions and to increase the solidification speed.

Table1: Chemical composition of A356.1

Element	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Cr**	**Ni**	**Pb**	**Sn**
Percentage	91.73	7.23	0.32	0.18	0.02	0.38	0.05	0.01	<0.01	0.05	0.02	0.01

For microstructural study, the as-cast composite samples were cut, mechanically ground, and finally polished down to 0.05μm, then sputtered with Au for better conductivity. The distribution of the nanoparticles and individual elements in the composite phases were investigated with a scanning electron microscopy (CAMSCAN-MV2300 MODEL) equipped with an EDS detector (OXFORD).

Brinell hardness (HB) tests were performed on a ((DVRB-M MODEL Eseway)) tester with a 2.5mm ball indenter. Brinell hardness, instead of Vickers hardness measurement was used because Vickers hardness would be affected by the reinforcements in an uncertain way depending on the reinforcement position under and around the indentation point. A load of 31.25 kgf was applied and maintained for 30 s. Three measurements were done on each kind of the specimens to ensure the accuracy of results.

Three cylindrical specimens from each kind of the nanocomposite samples with 13mm of diameter and 18.2mm of height were machined for uniaxial compression tests. The geometry of the compression cylinders was such that provided an aspect ratio of 1.4. Uniaxial compression tests were performed at room temperature using a testing system (1195 model made by Instron Company-England) at a constant strain rate of 0.1 s^{-1}. For each test, teflon sheets were applied between the die/specimen interface to minimize the adverse frictional effects and subsequent barreling during uniaxial compression.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Uniform particle distribution across the matrix has a significant effect on the composite properties, therefore is a critical and very important factor in composite manufacturing. Generally in stir casting method, the particles disperse uniformly in the melt, but particle clustering and sedimentation are more likely to be formed. Figure 1 shows X-ray map of this specimen that indicates homogenous dispersion of Zr element in the Al bulk.

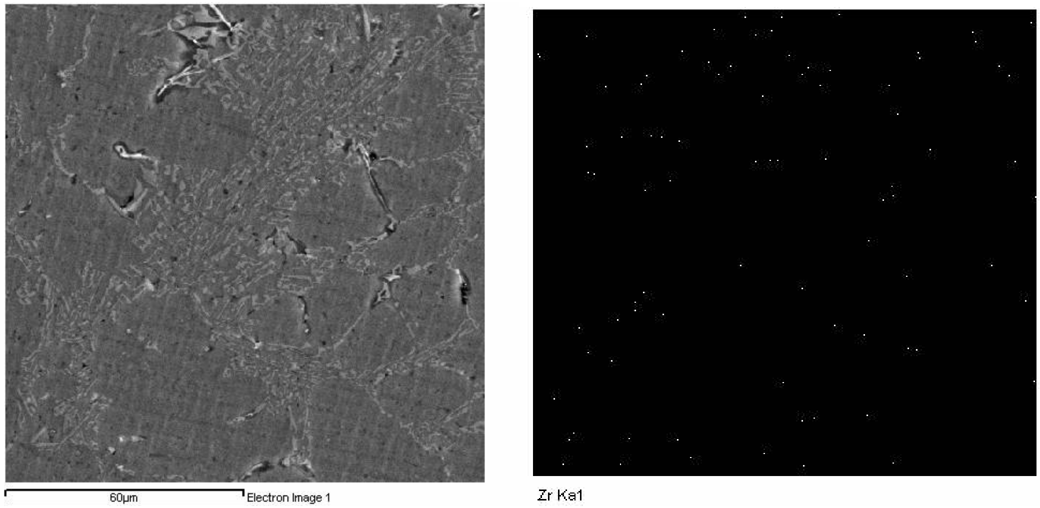

Figure 1: EDX dot-map for sample containing 5vol% ZrO_2 casted at 800ºC.

Figure 2 shows SEM micrographs of the composite containing 1.5 vol% nano ZrO_2 casted at 850°C. It displays that nano-sized ZrO_2 particles were well dispersed in the matrix; although some small clusters 100–300 nm remain in the microstructure.

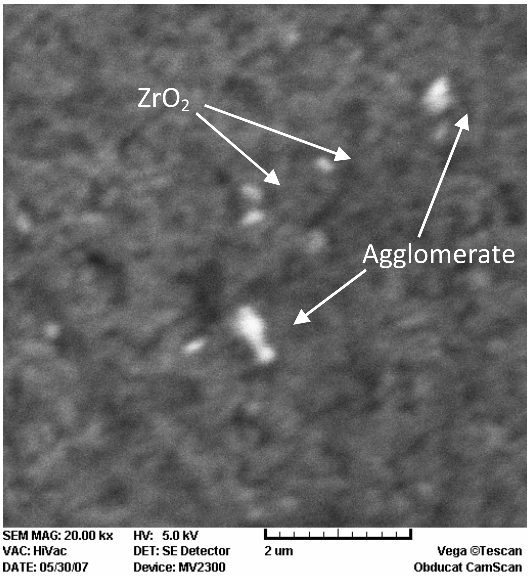

Figure 2: SEM image of Al/ZrO_2 nanocomposite sample containing 1.5vol% ZrO_2 casted at 850°C.

3.2 Mechanical Properties

3.2.1 Hardness measurements

Figure 3 shows the effect of nano-ZrO_2 volume fraction on hardness of Al/ZrO_2 composites. It can be seen that as a result of nano-ZrO_2 addition, the hardness of aluminum enhances. This is due to the higher hardness of nano-ZrO_2 particles. It also shows that nanocomposite samples casted at 850 °C exhibit higher hardness than other temperatures, and the highest hardness has been obtained in the specimens with 2.5 Vol. % nano-ZrO_2 powder casted at 850°C. Brinell hardness value of this specimen is reported 75.07 HB that in comparison with 51.48 HB of A356.1 aluminum, the hardness has increased up to 46%. The hardness reduction by adding more ZrO_2 powder is probably occurred due to the pore increasing in the interface of aluminum and ZrO_2 nanoparticles. Agglomerated particles and gas entrapment also can be considered as the hardness reducing factors.

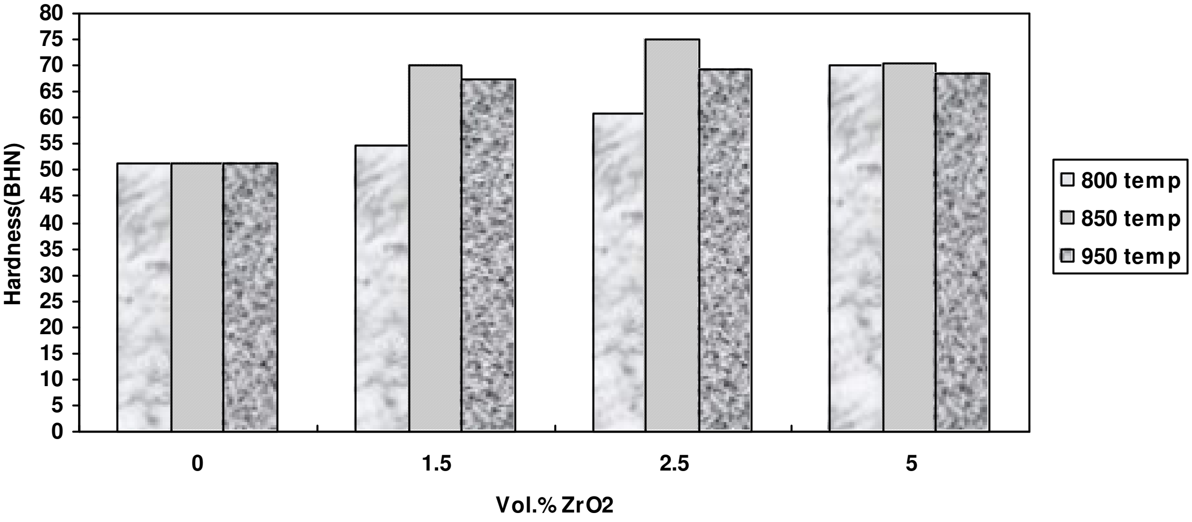

Fig. 3.The effect of ZrO_2 nanopowder addition on the hardness of A356.1 alloy.

3.3.2 Compressive yield strength measurements

The effect of ZrO_2 volume fraction and casting temperature on the compressive yield strength of nanocomposites is presented in figure 4. It shows that same as Brinell hardness results, presented above, the compressive yield strength increases with ZrO_2 volume fraction up to 2.5 vol% ZrO_2, but by adding more ZrO_2 nanopowder, the compressive yield strength remains constant even in some cases decreases. Assuming perfect bonding and uniform distribution of the particles, and no interaction effect between the deformation of the reinforcing phase and the matrix, the simplest approach to predict the deformation behavior of composite is through the classical rule of mixtures. But in most cases, the strength or ductility obtained from the experimental measurements seems to be considerably lower than that of the value obtained from the rule of mixture. This is primarily attributed to the existence of thermal mismatch stress generated due to difference in the thermal expansion coefficients between the matrix alloy and the reinforcing phase [23, 24], and ineffective load transfer between the phase constituents due to the presence of reaction product, relatively weak bonding, the presence of defects in the reinforcements, and the clustering of the particles [25-27].

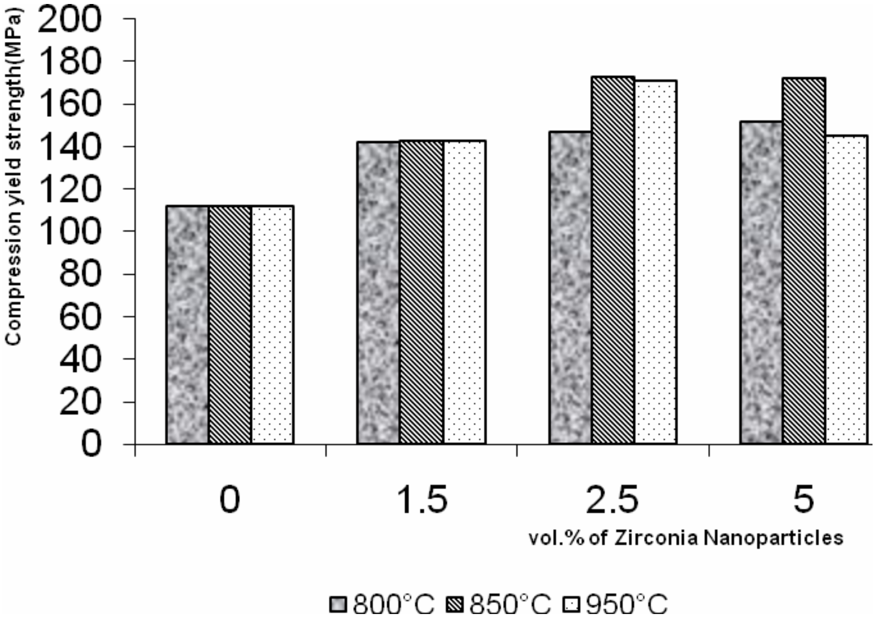

Figure 4: Effect of volume fraction of ZrO_2 and casting temperature on the compressive yield strength of nano composites.

It is expected that due to thermal mismatch stress, there is a possibility of increased dislocation density within the matrix which might lead to formation of local stress and also increase in strength of matrix, and thus to composite. This stress also depends on the temperature from which the composite is cooled. Thus, in the case of casting, the magnitude of thermal mismatch stress is expected to be considerably higher in this case that composite is cooled from its liquid stage. The tensile residual stress generated due to the difference in thermal expansion coefficients between matrix alloy and reinforcing phase is believed to enhance the compressive properties of composite more in comparison with tensile properties.

In the case of composites, the plastic flow of matrix is constrained due to the presence of these rigid and very strong ZrO_2 particles. The matrix could flow only with the movement of ZrO_2 particle or over the particles during plastic deformation. While 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. 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 ZrO_2 particles. The dislocation density in the matrix of the composite might be increased with increasing of ZrO_2. Similar fact is also true for plastic constrained to the matrix due to particle addition. This is the reason of increasing in compressive yield strength with adding

ZrO_2 content from monolithic alloy to 2.5 vol% ZrO_2. It may also be noted that a significant amount of dislocation, generated because of thermal mismatch stress or plastic incompatibility, gets neutralized due to the presence of incoherent weak interface between the particle and the matrix, and micro-porosities in the matrix. The amount of interface area and the micro-porosities increase with increasing of ZrO_2 content which might lead to lower flow stress in composite. Because of this fact, the compressive yield strength of the composite containing 5 vol% ZrO_2, compared with the 2.5vol% ones, has not increased.

4. CONCLUSIONS

1. Using the simple stir casting method, ZrO_2 nanoparticles are homogeneously dispersed throughout aluminum matrix.
2. The hardness and Compressive yield strength of Al/ZrO_2 nanocomposites are higher than that of A356.1 monolitic alloy.
3. Maximum value of strengthening is obtained in the nanocomposite samples containing 2.5 vol. %ZrO_2 and casted at 850 °C. Hardness of this nanocomposite has increased up to 46% in comparison with A356 monolitic alloy.

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