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Fabrication of nano-sized Al_2O_3 reinforced casting aluminum composite focusing on preparation process of reinforcement powders and evaluation of its properties

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ABSTRACT

In this study, a novel approach was used to fabricate Al_2O_3 nanoparticle reinforced aluminum composites to avoid agglomeration of nanoparticles in matrix. Al_2O_3 nanoparticles were separately milled with aluminum and copper powders at different milling durations and incorporated into A356 alloy via stir casting method. The effects of milling process and milling time on mechanical properties of the composites were evaluated by hardness, tensile, and compression tests. Based on the results, some of the composites, reinforced with Al_2O_3-metallic mixed powders, showed higher mechanical performance compared with that of the pure Al_2O_3 nanoparticle reinforced composite. This enhancement is related to uniform distribution of individual nanoparticles and grain refinement of A356 matrix, shown in microstructural studies. Moreover, the results showed that an increase in milling time, led to a gradual decrease in mechanical performance of the samples. It can be related to further oxidation of metallic powders that can act as inclusions and also further probable contamination of nanoparticles with increase in milling time. Studies on the fracture surfaces revealed that the failure of matrix was the basic mechanism of fracture in the composites. Agglomerated nanoparticles were observed on dendrites in the fracture surface of the Al_2O_3–Al reinforcement samples.

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1. Introduction

In lightweight metal matrix nanocomposites (MMNCs) a strong nano-sized ceramic reinforcement is incorporated into metal matrix to improve its mechanical properties including high specific strength, high specific stiffness and excellent wear resistance which make them attractive for numerous industrial applications. The mechanical properties of nanometric dispersion strengthened MMCs are far superior to those of micrometric counterparts with a similar volume fraction of particulates, moreover strength and ductility may be improved simultaneously if the dispersed particles are nano-sized [1,2].

Currently, there are several fabrication methods of MMNCs, including powder metallurgy, casting methods, in situ routes, chemical synthesis, etc. [2–6]. Among various techniques, mechanical alloying and casting techniques are more common than the other methods. Powders metallurgy is one of the useful techniques to achieve uniform distribution of nanoparticles. Separation effects and material contamination are less for this process, but the uniform dispersion of nanoparticle is lengthy and costly in this method. Furthermore solid state techniques seriously suffer from limitations in size and complexity of the components [7].

Compared with powder metallurgy, liquid state processing routes, like mechanical and electromagnetic stirring techniques and ultrasonic based dispersion have some important advantages such as wide selection of materials, better matrix–particle bonding, easier control of matrix structure, flexibility and excellent productivity for near-net shaped components, however it is extremely difficult to obtain uniform dispersion of ceramic nanoparticles in molten alloy due to poor wettability and a large surface-to-volume ratio of them, especially in viscose molten alloys, so particles have high tendency for agglomeration and clustering [2]. Generally nanoparticles are added into molten alloy during the process by manual handling and mechanical delivery. Yang et al. observed tendency of SiC nanoparticles to float on the surface of the molten Al when added. Therefore, they tried two different feeding techniques in ultrasonic dispersion method: master powder carrying and compressed inert gas spraying methods; however cluster of particles were formed [8]. The ultrasonic dispersion method is introduced to produce wide range of MMNCs. High-intensity ultrasonic waves generate strong non-linear effects in molten alloy, namely, transient cavitation and acoustic streaming. In the ultrasonic cavitation process, transient micro – hot spot with a

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temperature of about 5000 °C, pressure above 1000 atm and heating and cooling rates above 10^{10} K/s[18] can be formed. The strong impact coupling with local high temperature can break nanoparticle clusters, clean the particle surface, enhance their wettability and disperse nanoparticles into molten alloy [6,8,9]. It was difficult to utilize this technology for industrial applications and large quantity production. It is due to the ultrasonic flux density that is required for mass production of MMNCs (which is limited by the bulk of the molten alloy that is being processed). Recently, researchers have used a novel combined system included a simple mechanical pumping component with a radial impeller to force a large volume of melt to flow into an ultrasonic cavitation zone. This method enables small ultrasonic devices to be capable of large scale production of MMNCs and has a great potential in mass production of high-performance MMNCs for industrial applications [10].

Stir casting method is generally accepted as an alternative low cost and simple route which can be successfully used for mass production of MMCs. Due to particle agglomeration and clustering problems, achieving a uniform dispersion of nanoparticles is one of the principal purposes in the fabrication of MMNCs with stir casting methods. Furthermore, particles tend to sink or float according to their density relative to the liquid metal or will be pushed by the solidification front. Although it is a challenging subject, it would be advantageous to improve and optimize stir casting process to commercialize the production process of low-cost as-cast bulk light weight high performance components of MMNCs [11,12].

A356 alloy is a very commonly Si-containing hypo-eutectic aluminum alloy used as the matrix of aluminum matrix composites (AMCs) and characterized by: low cost, excellent casting characteristics, heat treatable, good strength and ductility. Al_2O_3 particles with high specific stiffness, superior high temperature and excellent mechanical properties are used as inert ceramic reinforcement phases in the AMCs; however the poor wettability of Al_2O_3 with molten aluminum is the major difficulty in achieving a uniform distribution of Al_2O_3 nanoparticles in the AMNCs [13]. In this research, a novel approach was used to affect particle distribution in matrix. Previous study has shown the beneficiary of milling process of Al_2O_3 nanoparticles with aluminum powders on uniform distribution of nanoparticles in A356 matrix [2]. The aim of the present work is to improve our knowledge about this approach by using various metallic powders in milling process and to evaluate the effects of milling time on mechanical properties of the composites.

2. Experimental procedure

A356 alloy with chemical composition, presented in Table 1, was used as matrix material and high purity Al_2O_3 nanoparticles (Ampco.Ltd.) with average size of 20 nm and micro aluminum and copper powders (Merck) with average size of 50 μm were used as components of reinforcement powders. The initial chemical composition of Al_2O_3 nanoparticles is presented in Table 2. Nanoparticles and metallic powders, in the weight ratio of $Al/Al_2O_3 = 1$ and $Cu/Al_2O_3 = 1$, were separately milled using a planetary ball mill (Fritsch, Gmbh), in uncontrolled atmosphere, wet situation, and within 1, 4, 8, 16, and 24 h. To fabricate A356/1.5 vol.% Al_2O_3 nanoparticle reinforced composites, an appropriate amount of pure and mixed Al_2O_3 powders wrapped in aluminum foils and added into molten alloy which was melted using a resistance furnace, equipped with a graphite stirring system, Fig. 1. The powder packets were added into molten metal when the vortex was formed at every 20 s. The packets melted and the particles started to distribute around the alloy sample. Composite slurry was stirred for 12 min, at the constant rate of 450 rpm [11–13], at 850 °C and poured into cast iron molds and shaped in the form of cylinders of 14 mm outer diameter and height of 140 mm. As cast specimens were heat treated (T_6) to the following schedule: 8 h at 495 °C, followed by 2 h at 520 °C, followed by water quenching (40 °C) and artificially aging for 8 h at 180 °C [14].

To study the microstructure of samples, the specimens were grinded through 240 up to 2500 grit papers followed by polishing with 0.3 μm alumina paste, cleaned by ultrasonic device, etched with Keller's reagent and coated with gold. Microstructural characterizations were carried out using field emission scanning electron microscope (HITACHI-S4160). Image analysis was carried out to determine the grain size of samples, according to ASTM E-112. The porosity content of the samples was determined by comparing the measured density (Sartorius-LA 230 S) with that of their theoretical density. To study the hardness, the Brinell hardness value of the samples was taken on the polished surface using a ball with 5 mm diameter at a load of 125 kg (Ernst-Twin) according to ASTM E10-12 standard. Each value of hardness is an average of at least forty randomly hardness readings in various longitudinal parts of a cylindrical sample (8 sections with 2 cm intervals in distance of 14 cm). To evaluate the tensile properties of the composites, the cylindrical samples were machined to tensile specimens according to ASTM: B557M standard and tested (Zwick-Z050). Extensometer (Instron-2620) was used to determine the Young's modulus of the samples. Fracture surfaces of tensile specimens, were studied using a scanning electron microscope (CAMSCAN-MV2300) To evaluate the compression strength, samples were prepared according to ASTM: E9-89 and were compressed (Instron-1195). Each value of

Table 1
The chemical composition of A356 aluminum alloy.

Composition	Al	Si	Mg	Zn	Cu	Fe
Wt.%	91.99	7.5	0.38	0.02	0.001	0.106

Table 2
The initial nano Al_2O_3 used powders analysis.

Composition	γ-Al_2O_3	Ca	Fe	Si	Co
Wt.%	>99.97	0.00016	0.00002	0.00035	0.00008

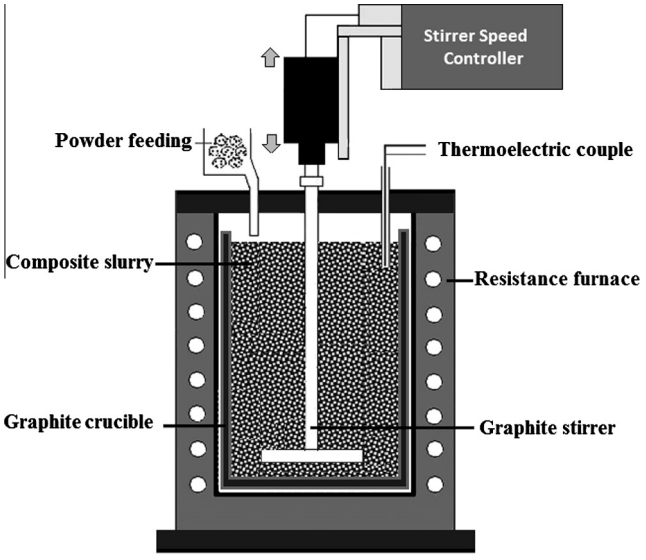

Fig. 1. Schematic design of stirring apparatus.

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