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Nano-sized aluminum oxide reinforced commercial casting A356 alloy matrix: Evaluation of hardness, wear resistance and compressive strength focusing on particle distribution in aluminum matrix

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ABSTRACT

Achieving a uniform distribution of reinforcement within the matrix is a challenge which impacts directly on the properties and quality of the composite material. In the present study a fabrication and evaluation approach was used focusing on particle distribution in metal matrix. Al and Cu powders were separately milled with nano-Al_2O_3 particles and incorporated into A356 alloy via vortex method to produce cylindrical A356/nano-Al_2O_3 composites. The stirring was carried out in various durations. The variations of density, hardness, compressive strength, and wear resistance were measured throughout the cylindrical samples. The evaluation of mechanical properties and microstructural studies showed that an increase in stirring time led to a more uniform dispersion of particles in the matrix and also led to a decrease in mechanical properties due to an increase in porosity content of the composites compared with those of the samples stirred for shorter durations. Moreover, milling process affected particle distribution. Nanoparticles more uniformly dispersed in the Al_2O_3–Cu reinforced samples compared with that of the samples reinforced with Al_2O_3–Al or pure alumina powders.

1. Introduction

In direct comparison with the monolithic aluminum alloys, AMCs offer a combination of higher stiffness-to-density ratio and elevated temperature, tensile, wear and fatigue properties. The size of particle reinforcements in AMCs generally ranges from a few nanometers to several hundred micrometers. The mechanical properties of nano-metric dispersion strengthened AMCs are far superior to those of micrometric counterparts. However, homogeneous distribution of particles is essential for achieving the improved properties in these composites [1–5].

Among the various methods, used to produce aluminum reinforced nano-Al_2O_3 composites, mechanical alloying and melt processing, are more common than the other routes. Nanocomposite powders fabricated by mechanical alloying of ceramic particles and Al-alloy powders may be used to produce such kinds of composites. In this way, subsequent and appropriate sintering procedure needs to be performed. Although the powder metallurgy techniques are more effective than the casting methods in terms of particle distribution, uniform dispersion of nano-sized ceramic particles is lengthy, expensive, and energy consuming in powder metallurgy techniques. Melt processing has some important advantages, such as: better matrix–particle bonding, easier control of matrix structure, simplicity, low cost of processing, nearer net shape and the wide selection of materials [6–8]. Stir casting, as an alternative and relatively simple rout can be successfully used to produce MMCs. In the case of particle reinforced MMCs, the distribution of ceramic particles in the metallic matrix is influenced by several factors. These include the rheological behavior of molten alloy, particle incorporation method, the interactions of particles and matrix before, during and after mixing and the changing particle distribution during solidification. The large differences in bulk properties (e.g. density) between particles and matrix materials play a significant role, as do the surface properties of the reinforcement powders. It is extremely difficult to obtain uniform dispersion of nano-sized ceramic particles in liquid metals due to high viscosity, poor wettability in the molten metals and a large surface-to-volume ratio of nanoparticles. Furthermore, when the particles are wetted in the molten alloy, they will tend to sink or float to the molten melt due to the density differences between the reinforcement particles and the matrix alloy melt, so that the dispersion of the ceramic particles is not uniform and the particles have high tendency for agglomeration and clustering. Regarding the mentioned challenges, achieving to uniform dispersion of nanoparticles is a principal purpose in production process of these

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types of reinforced composites. Based on the previous studies, nano-sized ceramic particles are almost always carried fully suspended in the liquid, and gravitational effects are negligible [9,10].

In this research a novel approach based on a previous study, which has shown the beneficiary of milling process of nanoparticles with aluminum powders on uniform distribution of nano reinforcements in matrix [11], was used to affect particle distribution in the matrix. Aluminum and copper powders were separately milled with nano-Al_2O_3 particles and incorporated into A356 alloy using vortex method. The hardness, wear and compression tests were carried out in different sections of the samples to primary evaluate the variations of mechanical properties of the composites with increase in stirring time and secondly to assess the fluctuation of mechanical properties in different sections of the samples, regarding the effect of quality of particle distribution in each sections of the cylinders on mechanical properties.

2. Experimental procedure

Aluminum alloy (A356), with chemical composition presented in Table 1, was used as matrix material. Nano-Al_2O_3 powders with average size of 20 nm (Ampco. Ltd.) and aluminum and copper powders (Merck Company) with average size of 50 μm were used as components of reinforcement powders. The powders were mixed in the mass ratio of $Al/Al_2O_3 = 1$ and $Cu/Al_2O_3 = 1$. Mixed powders were milled in a planetary mill for 4 h, in wet situation. To fabricate the composites, 500 g of A356 alloy was charged in a resistance furnace, equipped with a graphite stirring system. To produce A356/1.5 vol.% nano-Al_2O_3 metal matrix composite, an appropriate amount of mixed powders was wrapped in aluminum foils and added into molten alloy during stirring. The stirring process was carried out at the constant rate of 450 rpm for 4, 8, 12, and 16 min at 850 °C. The composite slurry was poured into cast iron mold and shaped in the form of cylinder of 14 mm outer diameter and height of 140 mm. The graphical scheme of mold and cylindrical specimen is shown in Fig. 1. The as-cast specimens were then 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 [12].

Table 1
Chemical composition of A356 aluminum alloy (wt.%).

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

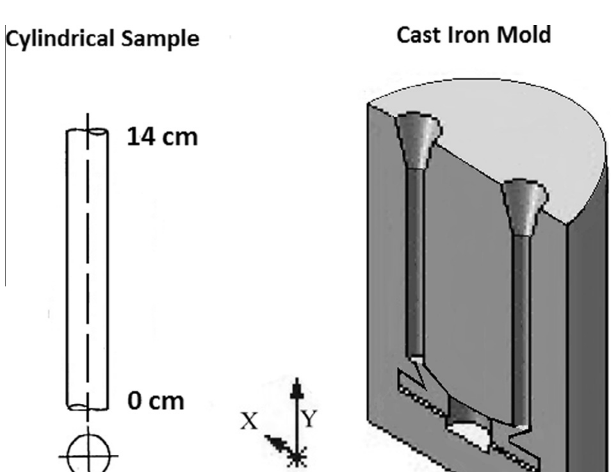

Fig. 1. Graphical scheme of mold and fabricated cylindrical specimen.

To study the microstructure of the specimens, samples were cut and prepared by grinding through 400 up to 2500 grit papers and then by polishing with 0.3 μm alumina paste and etched by Keller's reagent. Microscopic examinations of the composites were carried out using (HITACHI-S4160) field emission scanning electron microscope (FESEM). Image analysis was carried out to determine the grain size of samples. The porosity percentage of the composites was determined by comparing the measured density with that of their theoretical density. To study the hardness fluctuation in longitudinal parts of a cylindrical composite (hardness profile), Brinell hardness values of samples were measured by using a ball with 5 mm diameter at a load of 125 kg (Ernst-Twin, Model) according to ASTM E10-12 standard. Each value of hardness, which is reported, is an average of at least five randomly hardness readings. Wear test was carried out under dry condition on a pin-on-disc apparatus according to ASTM: G99-95A.

Dry sliding wear tests were conducted using a conventional pin-on-disc testing machine to appraise room temperature wear behavior of the Al-Al_2O_3 composites against a DIN 100Cr6 steel disk with a hardness of 62HRC. The pins, 5 mm × 15 mm, were in a conformal contact with the steel disk. The disc was rotated at a speed of 180 rpm. The test was carried out for constant distance of 600 m under the normal load of 7 N. The wear properties were measured in terms of weight loss of the materials, measured to 0.1 mg resolution. For the sake of accuracy, three samples were prepared by grinding and polishing and then tested and the mean value was reported. The worn debris were analyzed by a scanning electron microscope (CAMSCAN-MV 2300) equipped with an energy disperse X-ray analysis accessory. To evaluate the compressive strength, samples were prepared according to ASTM: E9-89 with height to diameter ratio of 1.5. The specimens were then compressed (Iinstron-1195) and the value of compressive strength were extracted from stress–strain curves.

3. Result and discussion

Fig. 2 shows nanoparticles in the surface of Al_2O_3–Cu mixed powders. The surface of metallic powders has been covered with fine nano-Al_2O_3 particles. In the case of particle size, Bouvard's model shows that the fine reinforcement particles cover the

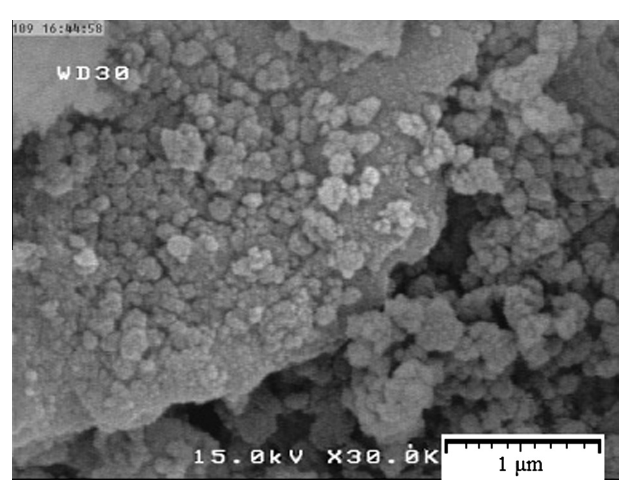

Fig. 2. SEM image of surface of Al_2O_3–Cu mixed powders.