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Microstructure and properties of functionally graded Al–Mg–B composites fabricated by centrifugal casting

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ABSTRACT

The microstructure and tribological performance of compositionally and functionally graded Al–Mg/AlB_2 metal–matrix composites (MMCs) produced by centrifugal casting have been investigated using Al–2wt.%Mg alloys containing 1, 2, 3, and 4 wt.% boron. Significant enrichment of aluminum diboride particles was observed in the external zone of the casting in the radial direction of the centrifugal caster. A corresponding increase in surface hardness as well as smaller wear volume in pin-on-disk wear tests were observed. The process provides a viable approach for lightweight, high wear resistance aluminum alloy components, particularly those with axial geometries.

1. Introduction

In composites made of functionally graded materials (FGMs) the volume fraction of the reinforcement phase(s) (or dispersoids) varies continuously in a given direction. This is achieved by using reinforcement particles with different properties, size and volumetric distributions, and morphologies in the matrix phase in a continuous manner. The resulting material exhibits gradual but continuous transition in engineering properties at the macroscopic or continuum scale [1]. This gradual transition allows a combination of properties without any mechanically weak interface, as would be the case if surface coatings were used. The gradual change in properties can be tailored to specific applications as, for example, those in which high wear resistance and high bulk toughness are required. However, special processing methods are required to produce FGMs with these characteristics that are not achievable in monolithic or homogeneous composite materials [2].

Centrifugal casting is one of the most effective methods for processing FGMs made of aluminum matrix composites (AMCs), because centrifugal forces cause heavier ceramic particles in the liquid metal to be displaced towards the outer surface of the casting [3]. In addition, centrifugal casting promotes very good mold filling combined with desired microstructural control, which usually results in improved overall mechanical properties [4]. Nevertheless, the underlying mechanisms governing reinforcement particle segregation and distribution are not fully understood. Also centrifugal casting contributes to lower costs by reducing the number of production steps when compared with surface modification and coating methods which have to be performed separately.

Al–B alloy system containing a few weight percent boron lends itself very well to be formed as a FGM. This alloy consists of an almost pure aluminum matrix with dispersions of AlB_2 particles, due to the negligible solubility of boron in aluminum. Currently, Al-rich alloys of this system are used as master alloys for grain refining of aluminum [5]. The resulting particle redistribution during centrifugal casting of Al–B alloys towards the outer zone of the casting is greatly facilitated by the higher density of the borides compared to the molten aluminum. The AlB_2 phase has a higher density, 3190 kg/m^3 [6], than liquid Al ($\approx$2400 kg/m^3) [7] at the semisolid composite casting temperatures (>700 °C). At this temperature most of the diborides remain solid. The forced segregation of hard borides towards the outer zones of the casting provides a unique approach to improve surface hardness [8] and wear resistance of FGM–AMCs.

Based upon those considerations, the present work reports the manufacturing of FGM–AMCs by centrifugal casting using Al–2%Mg alloys reinforced with AlB_2 particles. Microstructural characterization of these centrifugally cast composites was performed as a function of the position along the radial direction of the centrifugal caster as well as, for comparison purposes, on homogeneous gravity cast composites of similar compositions. Superficial Rockwell surface hardness and microhardness measurements as well as pin-on-disk wear tests were performed in order to evaluate

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the tribological performance of these compositionally graded composites.

2. Experimental procedure

As a first step towards producing centrifugally cast Al–Mg–B composites, investment casting molds were prepared by model making and mold construction. To fabricate the model wax blocks were used as they are easy to carve, have high detail reproducibility and possess a low melting point (105 °C). The wax model was machined to the dimensions of the final casting and encased in the cylindrical investment ceramic mold (hydrostone gypsum) made by the flask molding method. After drying the mold was dewaxed in a steam autoclave at 120 °C for 30 min.

The centrifugal casting machine used for this study is a spring-driven unit furnished with 88.9 mm diameter × 127 mm long flask sizes. Additionally, a 340 g capacity transfer scoop was utilized to pour the molten material, which subject to centrifugal forces, is driven into a mold placed in the flask (Fig. 1). The investment casting mold was preheated to 400 °C prior to centrifugal casting in order to facilitate the molten metal flow into the mold. The rotation speed was set at 20 G [9], while the pouring temperature of the alloy was 850 °C. This temperature was selected to provide enough superheat to facilitate the semisolid material flow into the mold.

The diborides particles originally are incorporated in the Al–B master alloy and remain in their solid state in the aluminum liquid matrix when it is mixed with Al–Mg alloys to obtain as a result overall composite compositions of Al–2%Mg with 1%, 2%, 3%, and 4% boron. Thus the boron content of the alloy was the primary variable investigated, while other process parameters also important to centrifugal casting such as temperature, rotational velocity, and Al-diboride particle size were kept constant for all the sample heats prepared for this study. Homogeneous gravity cast alloys devoid of compositional gradients were produced under similar conditions of temperature and boron contents to bench mark microstructural and property effects of centrifugal casting.

The 16 mm diameter and 25 mm long cylindrical castings (Fig. 2a) were cut at 0 mm (referred to as the −5 to 0 mm section), 5 mm (referred to as the 0–5 mm section), 10 mm (referred to as the 5–10 mm section), 15 mm (referred to as the 10–15 mm section), and 20 mm (referred to as the 15–20 mm section) cross-sections along the axial direction of the centrifugal casting (the radial direction of the centrifugal caster), as shown in Fig. 2b. According to this figure, the 0 mm cross-section corresponds to the outer surface of the axially the innermost section (−5 to 0 mm) of the casting and the 20 mm cross-section corresponds to the outer surface from the outermost section (15–20 mm) of the casting. This allowed for longitudinal mapping of the microstructure, hardness, and wear resistance along the centrifugally cast piece.

Microstructure, volume fractions of reinforcement particles and porosity, Rockwell superficial hardness, Vickers microhardness, reinforcement particle size and matrix grain size, as well as wear rates were evaluated for the various test sections illustrated in Fig. 2. Microstructural analysis was performed using a Nikon Epip-

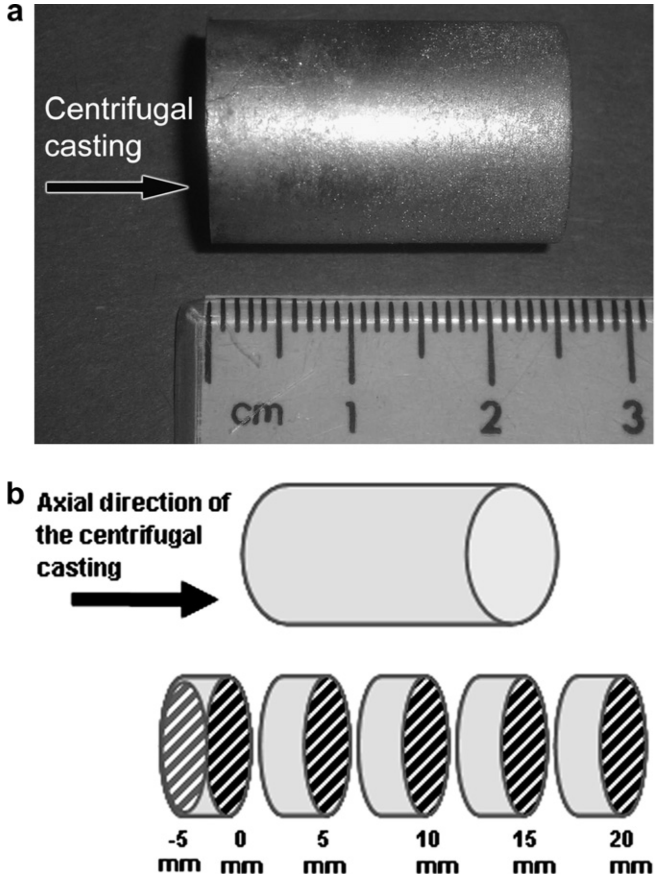

Fig. 2. Centrifugally cast piece (a) final specimen after centrifugal casting (b) test sections on which characterization and testing were performed.

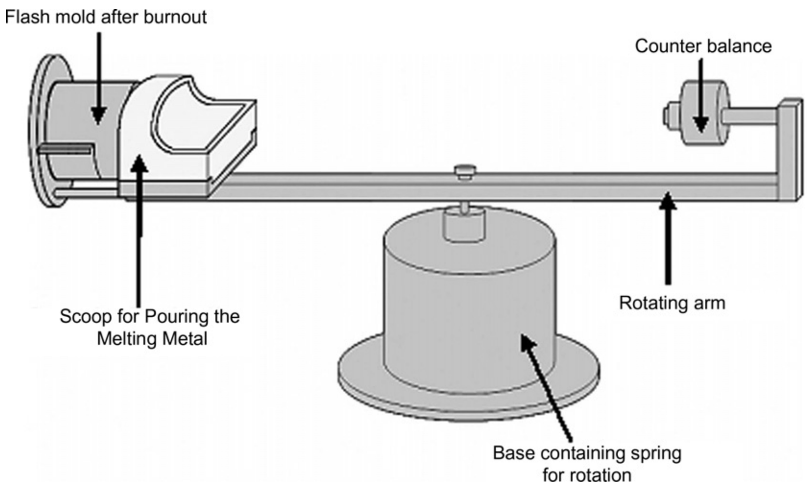

Fig. 1. Schematic illustration of the centrifugal casting system used in this research.