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Original Research Article

Enhanced mechanical properties of in situ aluminium matrix composites reinforced by alumina nanoparticles



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ABSTRACT

In situ fabrication of metal matrix composites has various advantages such as the formation of clean particle–metal interface with strong bonding. In this study, three types of metal oxides powders (commercial TiO₂, commercial ZnO, and recycled Pyrex) were injected into a pure aluminium melt to fabricate in situ aluminium matrix composites. Through chemical reaction this process produces alumina nanoparticles which act as the reinforcing agent. The process steps investigated include liquid-state stir casting at 1123 K followed by a hot rolling process. SEM and FESEM microstructural characterizations, as well as EDAX analysis, were used to determine the reactions, which occurred between the molten aluminium and the metal oxides to form nano alumina particles as the reinforcement. Tensile and micro-hardness tests were also performed on the rolled composites, to identify the effect of metal oxide type and amount, on the mechanical properties of the produced composites. It was found that using recycled Pyrex crushed powders led to the formation of a uniform distribution and reinforcement of alumina nanoparticles, while fine-micron ZnO and especially TiO₂ powders did not uniformly distribute in the melt.

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1. Introduction

Metal matrix composites (MMCs) have significantly better mechanical properties than the base alloy alone [1]. MMCs therefore play a crucial role in the automotive, aerospace, and other industries because of the improved specific mechanical

properties, the typically low cost of their reinforcements and the well-developed production methods [2]. Aluminium alloys have received the most attention as the matrix of MMCs due to their physical and mechanical properties [3]. Much research has been conducted to improve the structural and mechanical properties of the aluminium matrix nanocomposites (AMNCs) by the addition of nano-sized particles as reinforcement [4].

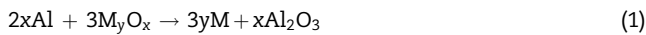
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Traditionally, reinforcements are added to a metallic matrix by an ex situ method [5], which provides a lower limit on the size of the reinforcing particles because of poor wettability between the reinforcement and the matrix due to increased surface area and the presence of surface contamination on the reinforcements [6]. To overcome these drawbacks, a method has been developed, in which reinforcements are established in the matrix by one or more chemical reactions, which is termed an in situ method [7]. In situ synthesizing can be obtained by many approaches such as reactive hot pressing (RHP), combustion synthesis or direct metal/metal oxidation (DIMOX) [8]. DIMOX process is based on a reaction between the pure metal and metal oxides (such as ZnO [7] and TiO₂ [9,10]), which is the most promising route for fabricating in situ reinforcements because of its simplicity, high-productivity and ease of control of the composite structure. Alumina, in particular, can be formed as reinforcement of the matrix using this method [11,12]. The general reaction of in situ AMNCs can be represented as [13]:



Various metal oxides can be used to produce in situ AMNCs, such as zinc oxide [7]. Kobashi and Choh [14] added zinc oxide powder to the molten aluminium. Subsequent work was accomplished by Chen and Sun [13], Yu et al. [15], Durai et al. [16], and Tavooosi et al. [17] in which zinc oxide was used to produce in situ AMNCs. Their results showed low reactivity between zinc oxide and molten aluminium due to the zinc oxide fine particle size and its poor wettability by aluminium. Maleki et al. [7] overcame this problem by developing a new method named activated powder injection (API), in which Al and ZnO powders were mixed and milled in a ball mill to activate the ZnO powders to react with the melt in a shorter time and at a lower temperature. Other advantages of this method are deagglomeration of the metal oxide particles during milling in a matrix of aluminium and increased wettability during injection into the melt due to the presence of an aluminium layer. Many other metal oxides such as NiO, TiO₂, Fe₂O₃, CuO, and ZnO have also been used as the source of oxygen to react with Al and form fine Al₂O₃ reinforcing particles in the aluminium matrix. Huang et al. [18] reinforced an aluminium matrix composite by a combination of in situ alumina particles with an average particle size around 0.5 μm and in situ alloying elements by using CuO and SiO₂ particles with an approximate particle size of 40 μm as the oxygen source. The experimental results of another research [19] showed that Al₂O₃ could be successfully formed with almost a particle size of 10 μm by addition of CuO (average particle size of 30 μm) into the melt. Yoshikawa et al. [20] produced an Al/Al₂O₃ in situ composite via a reaction between SiO₂ (fused silica rods) and molten aluminium. The mean particle size of obtained alumina was obtained to be in the micron range.

In this study, three types of oxide powders were used to study the fabrication of in situ AMNCs. TiO₂ and ZnO oxides were purchased as commercial powders. In addition, in order to examine if recycled oxides can be used as a promising source for fabrication of low-cost in situ AMNCs, Pyrex crushed powders were also used as the third type of oxide particles. The metal oxide powders were ball-milled with pure aluminium

powders before the casting process. Microstructural and mechanical properties of the final composites were compared to develop the DIMOX method for preparation of valuable in situ AMNCs materials.

2. Materials and methods

An aluminium bar with purity of 99.8% (from Iralco Co., Iran) was used as the matrix. Also, aluminium powder (purity of 99.8%, from Khorasan Powder Metallurgy Co., Iran) with an average particle size below 20 μm, as well as TiO₂, and ZnO oxide powders with average particle size between 500 and 1000 nm (both from Millennium Co., China) were also used in the present study. Recycled Pyrex powders (sodium borosilicate glass) with the chemical composition as shown in Table 1 were obtained by ball milling of Pyrex using a Sepahan 84D planetary ball mill. Fig. 1a and b shows the morphology of crushed Pyrex powders after 5 and 30 min ball milling, respectively. In addition, Fig. 1c and d shows the as-received TiO₂ and ZnO powders with average particles sizes between 500 and 1000 nm. Considerable agglomeration can be seen for both the TiO₂ and ZnO as-received powders. Fig. 1a shows that large sized Pyrex powders with sharp edges were still present after 5 min milling, and that a longer milling time should be used for crushing. Fig. 1b shows that ball milling for the longer period of 30 min, with four 20 mm-alumina-balls, with the rotation speed of 550 rpm and under air atmosphere reduced the average particle size of crushed powders and produced a greater degree of particle sphericity compared to the 5 min milling period.

In order to deagglomerate the fine oxide particles, 15 g of each oxide powder (ZnO, TiO₂, and 30-min crushed Pyrex) were separately added to 15 g of pure Al powder and ball milled process for 2 h at a constant milling speed of 250 rpm under an argon (99.99% purity) atmosphere. The ball to powder weight ratio of 3:1 and the alumina balls (10 and 20 mm diameter) were used. To prevent the occurrence of excessive adhesion of the powders to balls and mill walls, stearic acid at 1 wt.% was used as a process control agent (PCA). After the milling process, to remove impurities, surface contaminations, and absorbed water molecules on the surface of the particles, as-milled powders were pre-heated under argon atmosphere for 2 h at 673 K using an ATBIN heat-treatment furnace, just before liquid-state stir casting process.

Four samples were prepared according to Table 2. A bottom-pouring stir casting system was used for the casting process [21]. For this purpose, 500 g of the pure aluminium bar was melted and heated to 1123 K, the powder particles were slowly added over a 1 min period, and the mixture of the aluminium melt and the milled powders was stirred for a further 5 min. This resulted in the formation of a uniform distribution of alumina-reinforcing nanoparticles.

Table 1 – Chemical composition of Pyrex 7740 glass (molar percent).

SiO ₂	B ₂ O ₃	Na ₂ O	Al ₂ O ₃	K ₂ O	MgO	CaO
80.8	12	4.2	2	0.6	0.2	0.2

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