Journal of Alloys and Compounds 649 (2015) 461–473

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

A novel aluminum based nanocomposite with high strength and good ductility

Hossein Ramezanalizadeh [a, *], Masoud Emamy [a], Mohammadreza Shokouhimehr [b]

[a] School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran
[b] School of Chemical and Biological Engineering, College of Engineering, Seoul National University, Seoul, South Korea

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
17 June 2015
Accepted 10 July 2015
Available online 13 July 2015

Keywords:
Composite materials
Nanostructures
Powder metallurgy
Tension test
Ductility
Fracture

ABSTRACT

Aluminum based nanocomposite containing nano-sized Al_3Mg_2 reinforcing was fabricated via mechanical milling followed by hot extrusion techniques. For this, Al and Al_3Mg_2 powders were mixed mechanically and milled at different times (0, 2, 5, 7, 10, 15 and 20 h) to achieve Al–10 wt.% Al_3Mg_2 composite powders. Hot extrusion of cold pressed powders was done at 400 °C with extrusion ratio of 6:1. Microstructures of the powders and consolidated materials were studied using transmission electron microscopy, scanning electron microscope and X-ray diffraction. Fracture surfaces were also investigated by scanning electron microscopy equipped with EDS analyzer. The results showed that an increase in milling time caused to reduce the grain size unlike the lattice strain of Al matrix. In addition, the fabricated composites exhibited homogeneous distribution and less agglomerations of the n-Al_3Mg_2 with increasing milling time. The mechanical behavior of these nanocomposites was investigated by hardness and tensile tests, which revealed it has four times the strength of a conventional Al along with good ductility. It was found that the ultimate tensile strength (UTS) and elongation of the nanocomposites were significantly improved with increases in milling time up to 15 h. This improvement was attributed to the grain refinement strengthening and homogeneous distribution of the n-Al_3Mg_2. Fracture surfaces showed that the interfacial bonding between Al and Al_3Mg_2 could be improved with increasing in milling time. Also HRTEM results from interface showed that a metallurgical clean interface and intimate contact between matrix and second phase. By extending the milling process up to 20 h, there was no significant improvement in mechanical behavior of materials, due to the completion of milling process and dynamic and static recovery of composite at higher milling times.

1. Introduction

Particulate-reinforced metal matrix composites (PRMMCs) have the potential to provide improved mechanical properties, for example, high specific stiffness and specific strength and creep resistance, which makes them attractive for applications in the aerospace, defense and automotive industries [1]. Among the various MMCs, Al-based composites are of interest because of their low density and good formability [2]. Metal matrix nanocomposites (MMNCs) which are usually mixtures of nanoparticles in a metal demonstrate new interesting properties [1]. The particles are supposed to act as obstacles to dislocation motion and to effectively pin grain boundaries, conferring therefore microstructural stability to the composite.

Nowadays, there are two methods to fabricate MMNCs. In one route, the melt technology needs that nanoparticles are dispersed in the melt of the metal matrix. This method is similar to the production of polymer nanocomposites and faces similar problems. The most important one is the poor wettability of the particles by the melt [1,3]. This limits the amount of reinforcing that can be properly dispersed [4]. In addition, due to the high temperature of the melt, chemical reactions take place at the interface between the second phase and the matrix, which in some cases leads to the formation of a brittle interphase which decreases the material performance. In second route, the most promising production technology is based on powder metallurgy (PM) [5]. The composites fabricated by normal powder metallurgy routes usually have weak interfaces between the second phase and the matrix. These interfaces tend to debond when subjected to an applied load, resulting in deterioration in mechanical behavior [6].

* Corresponding author.
E-mail address: hralizadeh@ut.ac.ir (H. Ramezanalizadeh).

http://dx.doi.org/10.1016/j.jallcom.2015.07.088
0925-8388/

One type of the powder metallurgy techniques is mechanical alloying or milling (MA/MM). The MA/MM process, using ball-milling techniques, has received much attention as a powerful tool for the fabrication of several advanced materials including equilibrium, nonequilibrium (e.g. amorphous, quasicrystals, nanocrystalline), and composite materials [7–9]. Also, MA/MM has produced notable improvements in the strength, toughness, fatigue life, and corrosion resistance of aluminum alloys [10].

This method requires mixing of two materials in powder form, mechanical alloying by ball milling followed by pressing, sintering, and/or hot pressing or extrusion. This method allows avoiding issues with miscibility and generally leads to sharp, mechanically strong interfaces between nanoparticles and the matrix.

Uniaxial cold-pressing is commonly used to densify the powder particles, of varied geometries, at low cost and with high productivity, providing cold-pressed powders that can be consolidated by sintering or hot extrusion. The latter has the advantage of promoting full densification [11]. Hot extrusion lets a high shear strain rate, providing a high-strength bonding between particles, and a microstructure very similar to that of a wrought product. In the case of aluminium and its alloys, hot extrusion breaks the typical oxide layer that coats the powder, providing better bonding of the particles [12]. In MMCs, hot extrusion tends to eliminate the clustering of reinforcing particles and therefore a better distribution through the metal matrix [13]. Various aluminum matrix composite systems with reinforcing phases of B_4C [14], SiC [1,4,5], Al_2O_3 [4], BN [15] and AlN [16], have been developed via various techniques. Other possible candidates as reinforcing agents in MMCs are complex metallic alloys (CMAs), intermetallic compounds with giant unit cells, comprising up to more than a thousand atoms per unit cell [17]. In fact, CMAs show many attractive properties for reinforcing applications, such as high strength to weight ratio, good oxidation resistance and high-temperature strength [17,18]. Among the various CMAs, the β-Al_3Mg_2 phase (with 1168 atoms per unit cell) [17,19] has been studied with special attention to its structure as well as to its physical and mechanical properties [17]. In addition, it is worthy to note that the Al_3Mg_2 has lower specific gravity of 2.25 g/cm^3 [17] (less than that of Al, 2.7 g/cm^3), compared to 3.95 g/cm^3 for Al_2O_3, 3.21 g/cm^3 for SiC, 2.51 g/cm^3 for B_4C and 3.51 g/cm^3 for diamond [20], which normally have been used as second phase in MMCs. These unique properties, along with other attractive properties such as high hardness and wear resistance [17], high-temperature strength (~300 MPa at 573 K [17]), and high capacity for hydrogen absorption [21], make Al_3Mg_2 a likely candidate as the reinforcing in an Al matrix composite.

Up to now, there is little work on the effect of novel reinforcing addition on the structural and mechanical behavior of MMNCs. Scudino et al. propound an idea for applying CMAs as new reinforcements instead of conventional reinforcing materials [19].

In this work, we study the effect of Al_3Mg_2 nanoparticles and of processing conditions like milling time on the microstructural and mechanical behavior of the composite. The powder is consolidated using cold press and then vacuum sintering followed by hot extrusion. The mechanical behavior of the composites is probed by performing uniaxial tensile tests and microhardness measurements. Moreover, comparative study of hardness, UTS and elongation values of the nanocomposite material will be done relative to the pure Al.

2. Experimental

Nominal composition of the selected Al_3Mg_2 was $Al_{60}Mg_{40}$ according to the phase Al–Mg diagram [22], shown in Fig. 1. According to this image, Al_3Mg_2 single phase could be formed as a stable phase from a congruent melt with melting point of 451 °C at

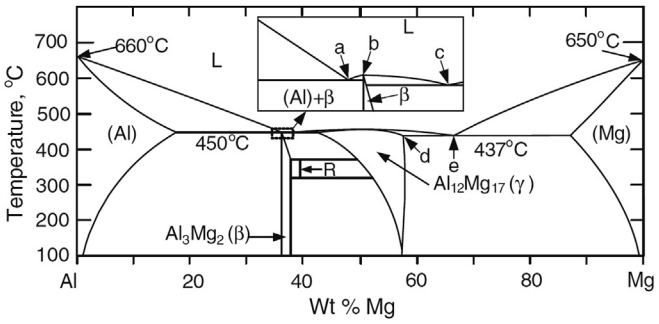

Fig. 1. Phase diagram of Al–Mg [22].

38.5–40.3 atomic percent range of Mg. In this study pure Al (>99.92%) and Mg ingots (>99.90%), were used in a well atmosphere controlled furnace to prepare Al_3Mg_2 ingots. Then powders of Al_3Mg_2 were fabricated by mechanical milling of the broken ingot using an attrition ball mill with rotation speed of 400 rpm and ball to powder weight ratio of 12:1. The vial and balls were made of hardened chromium steel. In all experiments stearic acid (2 wt.%) was also added to the powder mixture as a process control agent (PCA). The milling operation was pursued in pure argon atmosphere (99.999%) to avoid the oxidation of the materials. Al powder, (63 μm, >99.90%), blended with 10 wt.% of β-Al_3Mg_2 powders were synthesized through mechanical milling technique. Table 1 shows the material compositions and milling conditions for this study. The phase compositions of milled powders were investigated by X-ray diffraction analysis (XRD) using a "Philips PW 1730″ X-ray diffractometer with $Cu_{K\alpha}$ filtered radiation and 2 deg/min scanning rate.

XRD data was also used to determine the crystallite size (D) and lattice strain (ε). The crystallite size was determined from the broadening (B) of the diffraction lines 1 1 1, 2 0 0, 2 2 0 and 3 1 1 using following Scherrer equation [23]:

$$D = \frac{0.9\lambda}{B\cos\theta} \quad (1)$$

The lattice strain (ε) was also calculated for the same diffraction lines from the following equation [23]:

$$\varepsilon = B/4\tan\theta \quad (2)$$

where, λ is wave length = 1.54059 Å ($Cu_{K\alpha}$ radiation), B is the full width at half maximum, θ is the angle in radians and d is d-spacing between the planes.

Particle size distribution was determined by laser particle size analyzer (CILAS 1064 Liquid), to determine the volume size distribution, D_{10}, D_{50} and D_{90} automatically.

Table 1
Materials composition and milling conditions used in this study.

Materials label[a]	Matrix	Al_3Mg_2 (wt.%)	Milling time (h)
Al	Al	0	0
AC10-UM	Al	10	0
AC10-2HM	Al	10	2
AC10-5HM	Al	10	5
AC10-7HM	Al	10	7
AC10-10HM	Al	10	10
AC10-15HM	Al	10	15
AC10-20HM	Al	10	20

[a] The symbol: "A" represents Al; the second symbol: "C" represents Composite, the third symbol: "H" represents Hour and the last symbol: "M" represents Milling. The first two digits designate the amount of Al_3Mg_2 and the next digits designate the milling time. The UM means Unmilled.