Journal of Alloys and Compounds 605 (2014) 131–136

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Letter

Dispersion of soft Bi particles and grain refinement of matrix in an Al–Bi alloy by equal channel angular pressing

Min Zha [a,*], Yanjun Li [a,*], Ragnvald H. Mathiesen [b], Hans J. Roven [a,c]

[a] *Department of Materials Science and Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway*
[b] *Department of Physics, Norwegian University of Science and Technology, 7491 Trondheim, Norway*
[c] *Center for Advanced Materials, Qatar University, Doha, Qatar*

ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form 8 February 2014
Accepted 17 March 2014
Available online 5 April 2014

Keywords:
ECAP
Particle dispersion
Al–Bi monotectic alloys
CDRX
PSN

ABSTRACT

The deformation behavior of a soft particle containing Al–8Bi hypermonotectic alloy during equal-channel angular pressing was studied. The size, shape and distribution of soft Bi particles are substantially modified via shearing, fragmentation, coalescence and ripening. It is found that the soft Bi particles have a strong influence on promoting refinement of Al grains via particle stimulated continuous dynamic recrystallization. The present work provides an effective methodology to obtain monotectic aluminium alloys with well-dispersed soft phase particles.

1. Introduction

Hypermonotectic Al–X (Pb/Bi/In) alloys have been considered for a long time as potential candidate for advanced bearings in automotive applications [1]. It has been reported that alloys with gross compositions above the monotectic one would be especially useful because then the volume fraction of the soft inclusions is sufficiently high to produce bearings with a drastically lower friction coefficient and a very small wear resistance compared with the standard alloys used nowadays in car engines: bronze and lead [1]. However, during solidification of Al–X alloys, phase separation occurs already in the liquid state [2–4]. Due to the large density differences between Al and soft X phases [2], and the complex agglomeration dynamics of the minority phase droplets [3], it has turned out difficult to obtain a well-dispersed and homogeneous distribution of the minority phase X by conventional casting methods in hypermonotectic Al–X (Pb/Bi/In) alloys [3,5,6].

Equal-channel angular pressing (ECAP), frequently used for fabrication of ultrafine-grained (UFG) materials, has recently been suggested as an effective method for improving the homogeneity of particle distributions and mechanical properties of as-cast composites [7,8]. For instance, ECAP processing has been reported to influence significantly the morphology and distribution of secondary-phase $Al_2O_3^-$ [8], $Si + Al_5FeSi^-$ [9] or CB_4 particles [10] in Al-matrix composites. The major challenge in application of Al-matrix composites and alloys containing hard particles is their limited ductility and formability, as cracks and voids tend to form and grow around the matrix–particle interface [9]. In contrast, it is interesting to note that super-ductility was achieved in a supersaturated Al–Zn alloy subjected to severe plastic deformation, due to the formation of lubricating Zn boundary layers that can provide lubrication and thereby facilitate easier GB sliding [10].

In addition, it is interesting to mention that Al–Pb composites were produced by strong extrusion (to 96% reduction in area) of compacted Al and Pb powders by *Brokmeier* et al. [11]. The results showed that the originally spherical particles in the Al–Pb alloy become elongated in the extrusion direction after extrusion. Therefore, it seems that the conventional extrusion deformation can not be served as an efficient method to disperse the soft particles in immiscible Al–X alloys.

However, studies of ECAP or other severe plastic deformation (SPD) processing of alloy composites with soft easily deformable secondary-phase particles distributed in a ductile hardenable matrix, to our knowledge, not been reported. Therefore, the aim of the present study is to investigate the influence of ECAP on the shape, size and distribution of soft secondary-phase particles and at the same time to clarify the role of these particles on grain refinement in hypermonotectic Al alloys during SPD process.

---

* Corresponding authors. Tel.: +47 98283973 (Y. Li). Tel.: +47 73597092 (M. Zha).
E-mail addresses: min.zha@material.ntnu.no (M. Zha), yanjun.li@ntnu.no (Y. Li).

http://dx.doi.org/10.1016/j.jallcom.2014.03.126
0925-8388/

2. Experimental procedure

Materials used for the present work were produced by melting 99.999 wt.% purity Al and Bi in a fiberfax coated clay–graphite crucible to a composition of Al–8Bi (wt.%), and cast in an insulated, bottom-chilled Cu mould with a diameter of 60 mm. Samples were machined to bars with dimensions of 19.5 × 19.5 × 50 mm^3. The bars were deformed in a 90° ECAP die giving a strain $\varepsilon = 1$ for each pass, employing the B_c route at ambient temperatures [12]. For comparison, bars having dimensions of 19.5 × 19.5 × 100 mm^3 cut from commercial purity Al ingot, having chemical composition (in wt.%): Mg 0.00087, Fe 0.0581, Si 0.0428, Ti 0.0262 with Al in balance, supplied by Hydro Aluminium were also pressed to corresponding strains. Graphite lubricant was used to lower the friction during ECAP. Samples for microstructure observations were cut from selected transverse and longitudinal sections of the uniformly deformed centre regions of the ECAP bars, and prepared by standard metallographic techniques followed by electro polishing conducted under established procedures [12]. For convenience, the Al–8Bi samples cut from bars deformed after 1, 4 and 5 passes are referred to as 1P, 4P and 5P sample, respectively. To gain better and more reliable electron backscattered electron (EBSD) and backscattered electron (BSE) SEM images, the electro polished samples were further ion milled for 30 min. by using focused ion beam at a gas flow rate of ~0.08 ml/min. In order to decrease the potential damage of the crystal lattice upon exposure of the focused ion beam, a low voltage of 3–3.5 V and a high tilt angle of ~70° were applied during ion milling. EBSD studies were carried out in a Zeiss 55VP FEG-SEM equipped with a Nordif electron backscatter diffraction (EBSD) detector. TSL OIM software [13] was used for the analysis of the EBSD images. EBSD characterization was performed with 20 kV acceleration voltage, 20 mm working distance, 70° tilt, and with 0.05–0.2 μm scan steps. The equivalent circular diameter, volume fraction and the aspect ratio of the Bi particles in the Al–8Bi alloys are measured using the Image J software [14] on 4 BSE images at 500× magnification for each sample.

3. Results and discussion

3.1. Redistribution of the soft Bi particles

Typical backscattered electron (BSE) SEM images taken from the cross section and the longitudinal section of samples prior to, and after ECAP deformation are shown in Fig. 1. The white spheres are Bi particles while the darker areas represent the Al matrix. Some pores (black regions) exist in the microstructure, which most likely are caused by the depletion of Bi particles during the mechanical and/or electro polishing. The spatial distribution of Bi particles in the as-cast material is very inhomogeneous (Fig. 1(a) and (d)). Especially in the longitudinal section, the Bi particles have an obvious elongated network distribution. After 1 pass of ECAP, Bi particles are significantly dispersed in both sections, and the dispersion in the longitudinal section is more remarkable (please compare Fig. 1(b–e)). Some elongated Bi particles and coarse Bi particles (indicated by arrows) can be observed. The formation of these particles is ascribed to the merging of finer particles during ECAP deformation. With further increasing the number of ECAP passes, the dispersion of Bi particles is slightly improved. As shown in Fig. 1(c) and (f), after 5 passes of ECAP, the distribution of Bi particles is more dispersed than 1P sample, but there is not a significant change on the size and shape of the particles. It indicates that 1 pass ECAP seems sufficient to disperse the Bi particles in the

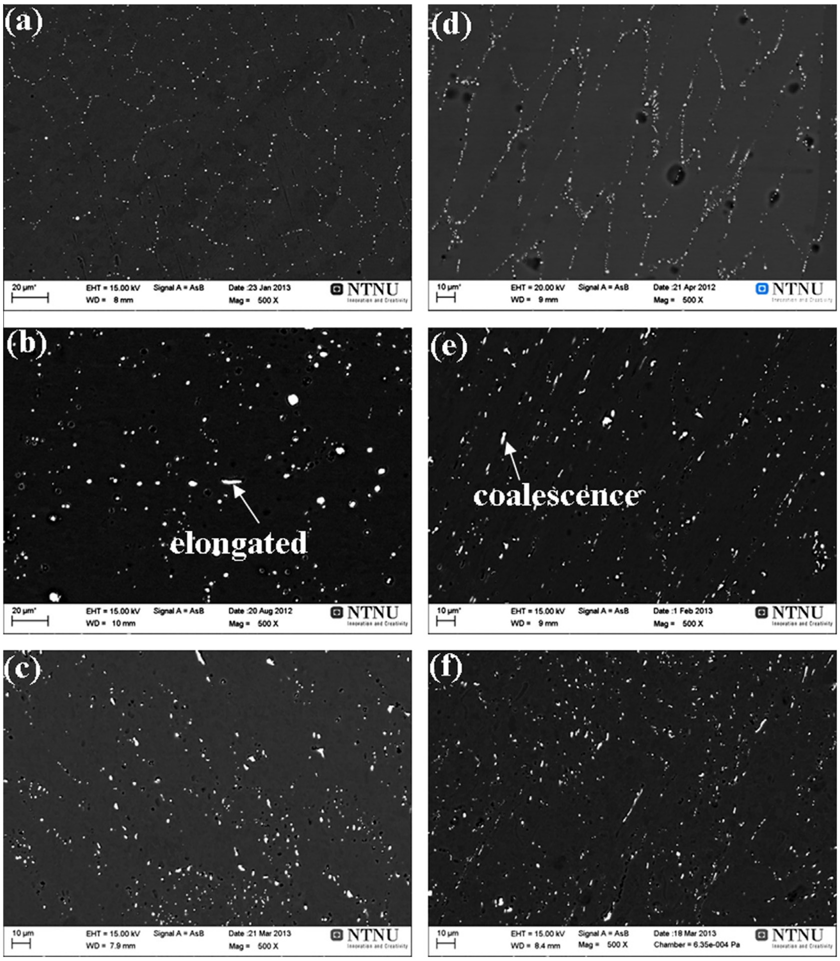

Fig. 1. BSE micrographs of the Al–8Bi alloy in different conditions: (a) and (d) as cast, (b) and (e) 1 pass, (c) and (f) 5 passes; (a)–(c) are taken in the cross section while (d)–(f) are in the longitudinal section.