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Effect of soft Bi particles on grain refinement during severe plastic deformation

Hai-long JIA, K. MARTHINSEN, Yan-jun LI

Department of Materials Science and Engineering,
Norwegian University of Science and Technology, Trondheim 7491, Norway

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Abstract: Two aluminum alloys, Al−8Zn and Al−6Bi−8Zn were subjected to equal channel angular pressing (ECAP) up to 5 passes at room temperature. The microstructural evolution and the grain refinement behavior of these alloys were systematically studied by electron backscatter diffraction (EBSD). After 5 passes of ECAP, ultrafine grained microstructures formed in both alloys. However, the grain structure in the Al−6Bi−8Zn alloy is much finer than that of Al−8Zn alloy, showing that the soft Bi particles have a strong influence on enhancing the grain refinement during ECAP. The strengths of the ECAP-processed materials were measured by hardness test and it showed that after 5 passes of ECAP, the hardness of the Al−6Bi−8Zn alloy was higher than that of the Al−8Zn alloy. The effects of soft Bi particles on the deformation behavior during ECAP and the final strength of the Al−6Bi−8Zn alloy were discussed.

Key words: Al alloys; equal channel angular pressing (ECAP); Bi particle; grain refinement; hardness

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1 Introduction

Alloys with a miscibility gap in the liquid state, such as Al−Bi, Al−Pb and Al−In, are potential materials for the application in advanced bearings in automotive industry [1]. The so-called hypermonotectic alloys with gross compositions above the monotectic one would be especially useful because the volume fraction of the soft inclusions is sufficiently high to produce bearings with a drastically low friction coefficient and a very small wear resistance. Hypermonotectic Al−Bi (i.e. >3.4% Bi) alloys containing homogeneously distributed soft secondary phase Bi particles (melting temperature 271.3 °C) within an Al-enriched hardenable matrix can resist high pulsating loads and show good tribological properties. Recently, European Union has proscribed the use of Pb-containing alloys [2], so, hypermonotectic alloys have gained increased interest again. Therefore, developments of new Pb-free bearing materials are of great importance and alloys based on Al−Bi system are supposed to be good candidates to replace Al−Pb alloys. At the same time, another special advantage of the aluminum-based bearing materials is mass saving. So far, most of the research works have been conducted to understand the solidification behavior of Al−Bi alloys and improve the distribution of Bi particles by different methods [3−5]. For example, SILVA et al [6,7] studied microstructural development as well as thermal parameters during transient directional solidification of Al−Bi alloys.

Equal channel angular pressing (ECAP) has been used to produce ultrafine grained (UFG) materials at a relatively low cost for many years [8]. However, studies of alloy composites containing soft easily deformable secondary phase particles distributed in a ductile hardenable matrix processed by ECAP are few [9]. Recently, ZHA et al [9] investigated the deformation behavior of Al−8Bi alloy using ECAP and found that the soft Bi particles contribute to matrix grain refinement. But the strength of the binary Al−Bi alloy is too low, so the aim of the present study is to improve the strength of Al−Bi alloy (by adding Zn into the Al−Bi alloy). The influence of soft secondary phase particles on grain refinement in hypermonotectic Al alloys containing Bi during ECAP process was investigated. At the same time, the corresponding hardness was briefly reported.

2 Experimental

The materials used in the present work were Al−8%Zn and Al−6%Bi−8%Zn ingots which were

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Corresponding author: Hai-long JIA; Tel: +47-93682586; E-mail: hailong.jia@ntnu.no
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produced by melting 99.999% purity Al, Zn and Bi in a clay-graphite crucible and cast in an insulated and bottom-chilled Cu mould. It is noted that 0.5%Al−Ti−B grain refiner was added into the melt to get fine grains. Bars with dimensions of 100 mm × 19.5 mm × 19.5 mm were machined from ingots for the ECAP process. Before ECAP, to lower the friction during pressing, samples were coated with a thin layer of a graphite lubricant. Then, these bars were processed by ECAP though a 90° die via route Bc (samples was rotated by 90° in the same sense between each pass) at room temperature, which leads to an imposed equivalent strain of about 1.0 per pass [8].

Samples from the uniformly deformed central region of the ECAP-processed billets were chosen for microstructure observation and hardness test. The deformed structure was characterized on the longitudinal section by electron backscatter diffraction (EBSD). The samples were ground mechanically on abrasive papers containing SiC particles to a level of 4000 grit and finally polished with the 1 μm diamond paste. It is noted that prior to the EBSD examination, the sample surfaces were ion milled by using the Hitachi IM 3000 machine at a high tilt angle of ~70° and a gas flow rate of ~0.08 mL/min for 45 min at 3.5 V. EBSD was performed using a Hitachi SU−6600 field emission gun SEM (FEG-SEM) equipped with a Nordif EBSD detector and TSL-OIM software. The Vickers hardness measurements were performed using a DKV−1S Vickers hardness testing machine under a load of 1 kg with a loading time of 15 s. The hardness values obtained were averaged from at least 10 separate measurements to minimize the scatter. The equivalent circular diameter of the Bi particles was measured using the Image J software. Four BSE images for each sample were used for image analysis.

3 Results and discussion

3.1 Microstructural characterization

3.1.1 As-cast microstructure

As shown in Fig. 1(a), the microstructure of the as-cast Al−8Zn alloy consisted of α(Al) grains with an average size of ~50 μm which was almost the same as the grain size of the matrix of Al−6Bi−8Zn alloy. In Fig. 1(b), the black spheres were Bi particles. Some of the Bi particles were along the grain boundaries and some are inside of the grains of the matrix. The average size of the Bi particles was measured to be approximately 5 μm by using the Image J software.

3.1.2 Deformation structure after room temperature ECAP

EBSD analysis was conducted on the longitudinal section of the 1 pass and 5 passes samples and the corresponding maps of the deformation microstructure developed after ECAP are shown in Fig. 2. The black areas are Bi particles in Figs. 2(b) and (d).

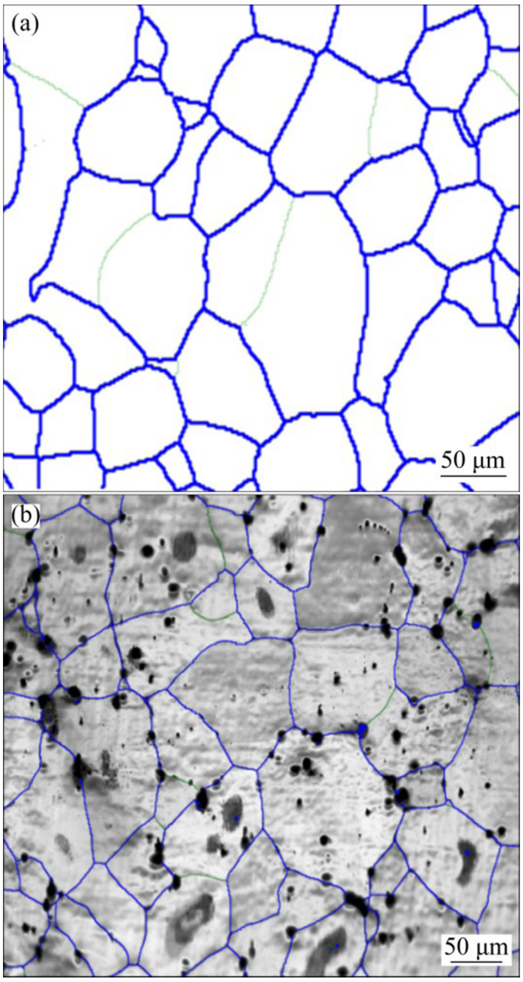

Fig. 1 Grain boundary map (EBSD) for as-cast Al−8Zn alloy (a) and image quality map (EBSD) for as-cast Al−6Bi−8Zn alloy (b) (Green and blue lines depict differences between neighbouring grid points 2°<θ<15° and 15°<θ<180°, respectively)

After 1 pass of ECAP, as can be seen from Figs. 2(a) and (b), the coarse equiaxed grains in the initial as-cast state of these two alloys were deformed into elongated grains (several hundred micrometers long) bounded by high angle grain boundaries (HAGBs), mainly aligned at an angle of ~30° to the extrusion direction (ED). It can be also seen that many low angle boundaries (LAGBs) and deformation bands were developed in the elongated grains. The formation of such deformation bands is energetically easier for a constrained grain to deform by splitting into regions, operating on fewer than the five independent slip systems required for homogeneous deformation and strain is distributed over the different bands so as to collectively maintain compatibility with its neighbors [10,11].