Available online at www.sciencedirect.com

SciVerse ScienceDirect

Acta Materialia 61 (2013) 3027–3036

Acta MATERIALIA

www.elsevier.com/locate/actamat

Room temperature equal-channel angular pressing of a magnesium alloy

C.F. Gu [a], L.S. Tóth [a,b,*], D.P. Field [c], J.J. Fundenberger [a,b], Y.D. Zhang [a,b]

[a] Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Université de Lorraine, 57045 Metz Cedex 1, France
[b] Laboratory of Excellence on Design of Alloy Metals for low-mAss Structures (DAMAS), Université de Lorraine, France
[c] School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920, USA

Received 17 October 2012; received in revised form 22 January 2013; accepted 29 January 2013

Abstract

Equal-channel angular pressing (ECAP) of magnesium alloy Mg–3Al–1Zn (wt.%) has been carried out at room temperature by applying a back-pressure three times larger than the yield stress in a 90° die. In a single pass, the initial grain size of ~10 μm originating from twin-roll casting was reduced down to ~3 μm. $\{1\,0\,\bar{1}\,2\}$ tensile twins were observed by orientation imaging up to ~40% volume fraction in grains that remained relatively high after ECAP. Regions with small grain size did not show twinning. The small lattice curvatures indicated that dynamic recovery/recrystallization took place during testing. The 90° ECAP deformation field was approximated by two-stage simple shear due to a large dead metal zone appearing at the outer corner of the die. Using this strain path, the viscoplastic self-consistent (VPSC) model was employed to model the texture evolution in the version where a parameter (α) tunes the interaction equation between a grain and the homogeneous equivalent medium. The textures were reproduced in good accord with experiments only if the α parameter corresponded to the Tangent VPSC model. Twinning was simulated in a quantitative way by introducing the volume transfer scheme in the VPSC model without employing a criterion for selection of the six possible twin variants.

Keywords: ECAP with back-pressure; AZ31; Polycrystal modelling; Simple shear; Tensile twin

1. Introduction

Light metals such as aluminium and magnesium alloys play a key role in structural applications to achieve weight and hence emission reductions. A frequently used magnesium alloy is AZ31 due to its high strength compared to pure Mg. One way to increase strength further is to reduce the grain size by employing severe plastic deformation (SPD) processes [1]. To transform initial large grains into an ultrafine-grained microstructure, equal-channel angular pressing (ECAP) is the most frequently used SPD technique, and is now commercialized in its continuous version [1,2]. Shaping by superplasticity also requires low grain size for which SPD is in general an efficient technique [3].

Compared with Al alloys, however, Mg alloys exhibit poor formability at room temperature due to their high critical stress for non-basal slip and twinning. Consequently, to use SPD for grain refinement in AZ31, the processing requires higher temperatures. After four-pass ECAP at 453 or 473 K superplasticity was obtained in AZ31 by Figueiredo and Langdon [3] in the temperature range of 623–723 K: tensile elongations of more than 1000% were achieved at strain rates equal to or less than 10^{-4} s^{-1}. Apart from these positive observations, Watanabe et al. [4] reported the ineffective superplastic capability of ECAPed AZ31 alloy due to microstructural instability at elevated temperatures. In conjunction with preliminary extrusion at different temperatures and speeds, Furui

---

* Corresponding author at: Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Université de Lorraine, 57045 Metz Cedex 1, France. Tel.: +33 604528208; fax: +33 387315366.

E-mail addresses: toth@univ-metz.fr, laszlo.toth@univ-lorraine.fr (L.S. Tóth).

1359-6454/$36.00 © 2013 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actamat.2013.01.063

et al. [5] conducted room temperature ECAP on a Mg–8% Li alloy using a die with a channel angle of 135°. They achieved additional grain refinement during ECAP since grain growth is limited at room temperature. Xia et al. [6] succeeded in deforming AZ31 at a temperature as low as 100 °C after pre-deforming it by extrusion at higher temperature. Using a 90° ECAP die, they applied a back-pressure of 50 MPa at a low extrusion speed (0.1 mm min^{-1}) and obtained a significantly refined microstructure together with an increasingly homogeneous grain size distribution. By applying a back-pressure of 125 MPa, Kang et al. [7] also demonstrated that the activation of non-basal $\langle c + a \rangle$ slip at 200 °C leads to efficient grain refinement, displaying increased strength and ductility after the ECAP process. Biswas et al. [8] deformed pure Mg by ECAP at room temperature after several ECAP passes at high temperatures. Using the viscoplastic self-consistent (VPSC) code, their simulation results indicated that the texture evolution can be reproduced mostly by slip if the grain size is sufficiently small. Based on the above, we conclude that deformation of AZ31 is possible at lower temperatures if this deformation procedure is preceded by a large plastic deformation at higher temperatures. So far there are no reports of room temperature ECAP on AZ31 alloy directly after casting. However, room temperature formability is an important issue because it can lead to smaller grain sizes with respect to warm- or high-temperature forming. Very high hydrostatic pressures seem to decrease twinning activity, which improves the formability of Mg alloys.

Twinning has been reported to provide plastic deformation along the *c*-axis in Mg alloys, and the critical resolved shear stress (CRSS) is even lower for twinning in Mg than for any slip mode except basal slip which has the lowest CRSS [9–12]. Thus, twinning in general is active in Mg and its alloys if the material is not highly pre-deformed. If large plastic strain at warm temperatures leads to significant grain refinement, macroscopic twinning is reduced due to the small grain size [13]. For modelling twinning in polycrystal plasticity, the most frequently used twinning approach in polycrystal simulations is the predominant twin system (PTS) scheme, in which a given grain is completely replaced by its predominant twin orientation if the twinning activity in the grain reaches a critical value [10]. This approach permits one to obtain relatively fair predictions of texture development but it is not physically realistic because only one twinning variant replaces the whole grain. Nevertheless, it is widely applied. For example, forming limit diagrams were modelled using the PTS scheme in AZ31 [11]. By coupling grain size changes with the occurrence of twinning, Barnett et al. [14] have demonstrated that the initial hardening plateau in AZ31 is due to twinning when grain size is sufficiently low. Guillemer et al. [9] have modelled the texture changes in low-cycle loading of pure Mg without physically creating twins in the simulation. Concerning the texture changes due to twinning, the volume transfer scheme proposed by Kalidindi [15] was first adopted by Gu and Toth [16] for low-cycle deformation of AZ31 at room temperature in the framework of the Taylor–Lin polycrystal model.

In this work, we aim to process the AZ31 alloy during room temperature ECAP and to investigate the microstructure evolution and texture changes of AZ31 by experiments and simulations. Room temperature 90° ECAP was conducted on the cast material by applying a high back-pressure of 400 MPa. The microstructure was characterized using electron backscatter diffraction (EBSD) and X-ray texture measurements. Polycrystal plasticity simulations were carried out by implementing the volume transfer scheme in the VPSC model for quantitative handling of twinning.

2. Experimental

The initial twin-roll casting AZ31 (Mg–3Al–1Zn, wt.%) alloy was homogenized at 470 °C for 2 h, resulting in an average grain size of ~10 μm. The billet of the solution heat-treated AZ31 was machined to 20 mm × 4 mm cross-section, 80 mm in length. At room temperature, the sandwich billet consisting of five layers was processed for one pass in a die of 90° angle with sharp corners using a back-pressure of 16 tonnes (400 MPa). The layers were stacked in the plane defined by the ED and ND directions (Fig. 1b), i.e. normal to TD, where ED, TD and ND mean extrusion, transverse and normal direction, respectively. The extrusion speed was 1 mm s^{-1} and colloidal graphite was used as lubricant during ECAP. The microstructure

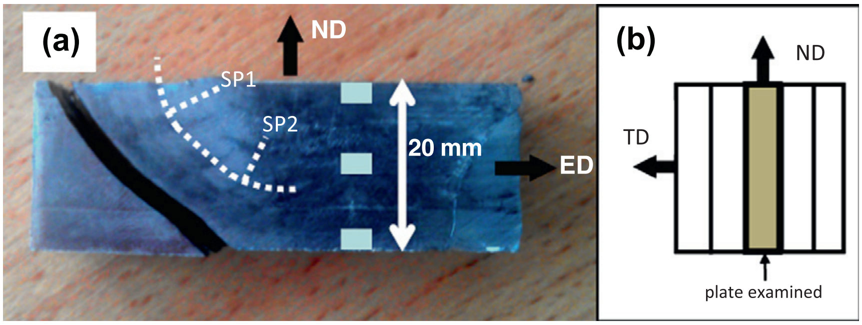

Fig. 1. The sample after one-pass ECAP by applying a back-pressure of 400 MPa at room temperature. (a) White rectangles show the positions of EBSD studies, at the top, middle and bottom regions in the central layer of the specimen. The dotted line is an approximate flow line; the corresponding positions of the two shear planes are also shown by SP1 and SP2. (b) The stacking orientation of the plates.