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Microstructure and tensile properties of Mg-3Al-1Zn sheets produced by hot-roller-cold-material rolling

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ABSTRACT

Mg-3Al-1Zn (AZ31) alloy sheets with various thickness reductions from 10% to 60% were fabricated in a single pass at 150 °C by hot-roller-cold-material rolling. The rolled sheets were then evaluated by microstructural characterization and tensile testing. The strength shows an increase with increasing thickness reduction from 10% to 40%, but the further increase in thickness reduction leads to a decrease in strength. Yield strengths of 273 MPa along the rolling direction and 357 MPa along the transverse direction are obtained for the sheet with 40% thickness reduction, which is characterized by highly elongated grains and high density dislocations, together with a few ultrafine, recrystallized grains in microstructure. The variation in strength with thickness reduction is discussed in light of the strengthening contributions from grain size and dislocation density.

1. Introduction

Magnesium (Mg) alloys have the potential of being used as lightweight structural materials to substitute steel and aluminium alloys, especially in the aerospace and automotive industries. However, the wider applications of Mg alloys have been restricted by their inadequate mechanical properties at room temperature [1]. It is well known that grain refinement is effective in improving the room temperature mechanical properties of Mg alloys [2–4]. As such, extensive efforts have been devoted to achieve ultrafine-grained microstructure in Mg alloys by applying various processing technologies [5–7]. Kim et al. [5] employed high-ratio differential speed rolling (HRDSR) to achieve a grain size of 0.6 μm for AZ31 (Mg-3Al-1Zn) sheet, which exhibited a high yield strength of 382 MPa. Chang et al. [6] obtained an extremely small grain size of 0.1–0.3 μm in AZ31 sheet by friction stir processing. Ding et al. [7] produced a grain size of 0.37 μm in AZ31 by equal channel angular extrusion (ECAE), which was accompanied by a high yield strength of 372 MPa. However, the above technologies are still at laboratory scale and not suitable for industrial production. Therefore, it is desirable to develop an efficient method that is not only capable of obtaining excellent mechanical properties but also applicable to large scale industrial production.

This paper reports the fabrication of high strength Mg-3Al-1Zn alloy sheets by an unusual rolling process, namely hot-roller-cold-material rolling, in which the rollers are heated rather than the material. During rolling, the higher temperature at the material surface than the centre compensates the loss of flow in the surface region due to friction and makes the deformation relatively uniform. Consequently, large plastic deformation can be achieved in one pass without causing surface cracking. In this work, AZ31 sheets with various thickness reductions are evaluated by microstructural characterization and tensile testing. The effect of thickness reduction on strength is discussed on the basis of microstructural observations.

2. Material and methods

Commercially available AZ31 sheets with a thickness of 3 mm were used as the starting material in this study. The rolling was performed at a constant rotation speed of 5 m/min with rollers of 220 mm in diameter. The as-received sheets were rolled in a single pass to thickness reductions of 10%, 20%, 30%, 40%, 50% and 60%, with the rollers heated to 150 °C. This temperature was the lowest temperature to achieve large thickness reductions in one pass without causing severe surface cracking. Tensile specimens with a gauge length of 25 mm and width of 6 mm were machined out of the rolled sheets along both rolling direction (RD) and transverse direction (TD). Tensile tests were performed at room temperature using Instron 5569 testing machine with an initial strain rate of $10^{-3}\,s^{-1}$. To ensure the repeatability of test results, three specimens were used for each condition.

Dislocation density was calculated using the diffraction profiles

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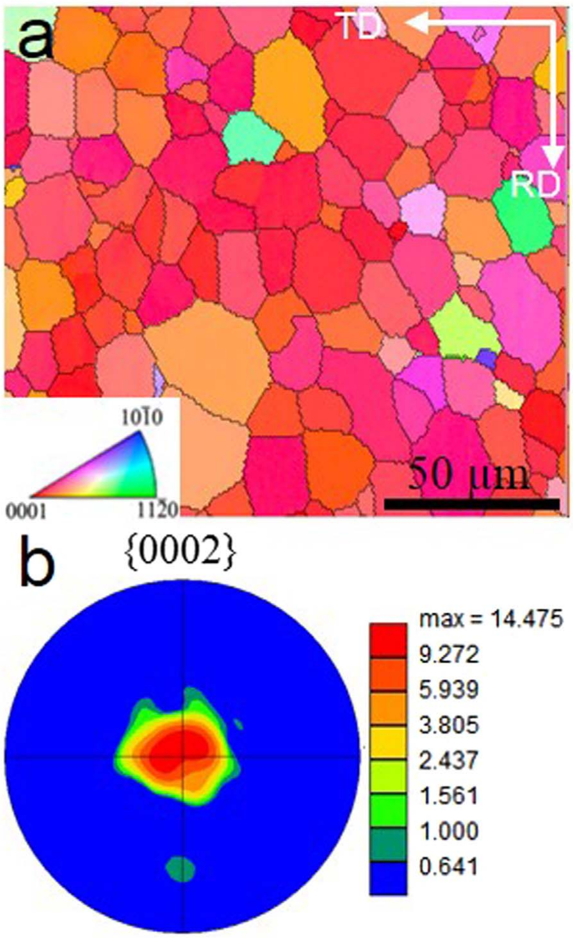

Fig. 1. EBSD maps of the as-received AZ31 sheet: (a) orientation map and (b) {0002} pole figure.

which were measured by a Bruker D8 Advance X-ray diffractometer using monochromatic Cu-Kα radiation (λ = 0.154 nm) operating at 40 kV and 40 mA. The diffraction lines were recorded from 30° to 90° with a step size of 0.005°. The X-ray diffraction (XRD) experiments were quantitatively analysed by TOPAS 4.2 software (from Bruker AXS). Macro-texture was also performed by XRD in GBC mini-materials analyser diffractometer using Cu-Kα radiation operating at 40 kV and 25 mA. The (0002), (10 $\bar{1}$ 0), (10 $\bar{1}$ 1) and (10 $\bar{1}$ 2) pole figures were collected on a 5° grid up to 75° sample tilt. Corrections for peak defocusing and background intensity were made using the experimentally determined defocusing curves from a powder samples with random texture. Data were analysed using the Textools software to generate orientation distributions and pole figures.

Electron backscatter diffraction (EBSD) was conducted on the rolled sheets using an FEI Quanta 3D-FEG scanning electron microscope. The samples for EBSD were cut with the broad surface parallel to the sheet surface. After grinding with SiC paper and polishing with 0.05 μm silica suspension, the samples were etched by argon ion beam at 7 keV for 5 min in a Gatan precision etching and coating system (PECS) prior to EBSD scanning. The rolled sheets were also examined by transmission electron microscopy (TEM) in an FEI Tecnai-T20 microscope. For TEM examinations, discs of 3 mm diameter and 0.15 mm thickness were cut from the centre portion of the rolled sheets. The TEM foils were prepared by twin-jet electropolishing at 100 V and −45 °C in a solution containing 5.3 g lithium chloride, 11.16 g magnesium perchlorate, 500 ml methanol and 100 ml 2-butoxy-ethanol.

3. Results and discussion

3.1. Effect of thickness reduction on microstructure

The EBSD characterization of the as-received AZ31 sheet is shown in Fig. 1. The microstructure consists of well-recrystallized grains with a grain size of ∼ 17.4 μm. The pole figure indicates that the sheet has a strong basal texture, with the basal pole of most grains aligned to the normal direction of the sheet.

Fig. 2 shows the EBSD orientation maps and XRD pole figures of the sheets with various thickness reductions. When the thickness reduction is below 40%, the microstructure is mainly characterized by deformed grains with twins, with no clear sign of dynamic recrystallization (DRX). DRX appears to occur in the sheets with 40–60% thickness reductions. While the 40% sheet exhibits partial DRX that is evidenced by the inhomogeneous microstructure (Fig. 2d), well-developed DRX microstructures are observed in the 50% and 60% sheets. The variation of average grain size with thickness reduction is shown in Fig. 3. The grain size is reduced from 17.4 μm in the as-received sheet to 2.8 μm when the thickness reduction increases to 60%. All rolled sheets still exhibit strong basal texture, probably because the rolling temperature is not very high. It is worth mentioning that the texture intensity increases from 14.5 mrd to 20 mrd when the thickness reduction is increased from 10% to 30%. With further increase in the thickness reduction, however, the texture intensity shows a gradual decrease.

XRD 2θ scan was performed to measure the effect of thickness reduction on dislocation density. The diffraction profiles were analysed by assuming that the peak broadening is related to the refinement of grains and the microstrain induced by dislocations [8]. The microstrain analysis was conducted using TOPAS software, which is based on the Gaussian-Lorentzian convolution with a width dependence on *tan* (*θ*) using a whole pattern fit and the Double-Voigt approach [9–11]. The detailed description of TOPAS can be seen in Wiessner's work [12]. Dislocation density, ρ, was subsequently estimated from the microstrain, *e*, according to the following equation [13]:

$$\rho \cong \frac{4\pi e^2}{Cb^2} \quad (1)$$

where C is the dislocation contrast factor that was determined as 0.19483 by Dragomir's work [13] and b is the Burger's vector (3.2 × 10^{-10} m for Mg [14]). The calculated values of dislocation density for the rolled sheets with various thickness reductions are shown in Fig. 4. The dislocation density is found to increase with increasing thickness reduction up to 40%, followed by a continuous decrease with further increase in thickness reduction.

Fig. 5 shows the TEM micrographs of the sheets with 10%, 40% and 60% thickness reductions. These images were taken from the RD-TD plane of the rolled sheets. As having been characterized by EBSD, the microstructure in the 10% reduction sheet consists of deformed grains with twins, which are typical low temperature deformation features of Mg alloys. Elongated grains and high density dislocations are present in the 40% thickness reduction sheet. Besides the deformed grains, a few grains with sizes ranging 0.1–0.3 μm are occasionally seen, indicating the occurrence of DRX. With thickness reduction increased to 60%, the microstructure consists of fully recrystallized grains of 1–3 μm and there is a significant decrease in the dislocation density as a result of DRX.

The above microstructural observations reveal that increasing thickness reduction in the hot-roller-cold-material rolling of AZ31 not only reduces grain size but also leads to changes in dislocation density; especially, ultrafine and well-recrystallized grains are developed in the sheets with 50–60% thickness reductions. The occurrence of DRX during the hot-roller-cold-material rolling explains why large thickness reductions as high as 60% can be achieved in one pass without causing severe surface cracking.