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Grain size and texture control of Mg–3Al–1Zn alloy sheet using a combination of equal-channel angular rolling and high-speed-ratio differential speed-rolling processes

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The texture and grain size of a Mg–3Al–1Zn alloy sheet were controlled by applying equal-channel angular rolling and high-speed-ratio differential speed rolling in sequence. A texture that has rarely been reported in any other sheet fabrication processes was developed in which some fiber axes of the largely weakened basal fiber texture tilted with spreading in the rolling direction. The microstructure and texture correlated well with the mechanical responses.

Keywords: Rolling; Severe plastic deformation (SPD); Magnesium alloys; Ductility; Texture

Magnesium alloys with a hexagonal close-packed crystal structure exhibit limited formability at ambient temperature due to the limited number of active slip systems. However, it was shown that they could be exceptionally ductile at room temperature through texture control using equal-channel angular pressing (ECAP) [1,2], whereby a tilted basal texture with *c*-axes inclining at ~45° with respect to the extrusion direction was obtained. The ECAP process is, however, inadequate to fabricate wide Mg sheets for use in the automobile and electronic device industries, since the sample should be in bulk form. In attempts to improve the tensile ductility of Mg alloys in sheet form, equal-channel angular rolling (ECAR) [3] and differential speed rolling (DSR) have been studied [4,5]. Cheng et al. [3] used the ECAR process to produce AZ31 Mg alloy sheets with improved ductility by tilting basal planes from the rolling surface toward the rolling direction by ~45° during shear straining at a sharp corner in the ECAR mould. In contrast, the DSR process improved the tensile ductility primarily by reducing the intensity of the ND//(0 0 0 1) basal fiber texture with slight tilting of the basal fiber texture (by less than 10°) [4,5]. Recently, the high-speed-ratio differential speed rolling (HRDSR) technique was developed to induce a large shear deformation in a magnesium sheet during rolling. When the speed ratio was set at 3, the average effective strain accrued during a single rolling pass for a 70% reduction in thickness was ~3.5 [6,7]. By using this technique, an ultrafine-grained microstructure with a low intensity of basal fiber texture could be obtained, leading to production of Mg alloy sheets with high strength and high ductility [6].

The present work has two main components. First, texture development and microstructure evolution during ECAR for different passes were examined in detail. Then the effect of application of HRDSR to the ECAR samples was studied. By properly controlling the thickness reduction ratio for HRDSR, one could obtain the unique texture where the texture characteristics of ECAR and HRDSR coexisted. Secondly, the effects of grain refinement and controlled texture on mechanical properties of the deformed samples were investigated and the result was discussed.

The initial material used for this study was an AZ31 magnesium alloy sheet of size $800 \times 120 \times 1.9\ mm^3$ (length × width × thickness) prepared by symmetric rolling. The sheet was heated at 623 K for 10 min, then rolled into the ECAR device with an ECAR mould having the

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oblique angle (θ) of 115°. The effective strain accumulated during ECAR per pass was estimated as 0.67 [8,9]. The twin roller and the channel were not preheated. The ECAR deformation was performed in one or three passes. In applying the three ECAR passes, the sheet was rotated by 180° along the rolling direction between the passes with the rolling direction unchanged. The ECAR samples were subsequently rolled by HRDSR, where the top roll rotated with a speed of 1 rpm in the counterclockwise direction while the bottom roll rotated with speed of 1/3 rpm in the clockwise direction, to different thickness reductions of 15%, 30% or 70% by a single pass under non-lubricated condition. The rolling direction of ECAR was unchanged during HRDSR. The ECAR samples were preheated at 473 K for 10 min before the application of HRDSR and the surface temperature of the rolls was maintained at 473 K throughout the rolling operation. The effective strains accumulated during HRDSR for different thickness reduction ratios of 15%, 30% and 70% were 0.35, 0.84 and 3.51, respectively, according to calculations using the finite element method, as studied in a previous work [7].

The development of textures was analyzed at the top roll side surface ($s = 1.0$), the center ($s = 0.0$) and the bottom roll side surface ($s = -1.0$) layers of the rolled sheets. Three pole figures, of $\{0002\}$, $\{10\bar{1}0\}$ and $\{10\bar{1}1\}$, were measured up to a tilt angle of 75° using the Schultz reflection method. The complete pole figures were calculated using the commercial software of LaboTex 3.0 without considering specimen symmetry.

The initial material and the deformed microstructures were examined by optical microscopy. The grain size was measured on the longitudinal cross-sections of the sheets. Mean grain sizes (d) were calculated from the optical micrographs using an image analysis program.

Tensile testing was conducted using specimens with a dog-bone geometry, with 8 mm gauge length along the rolling direction (0°) and at angles of 45° and 90° (i.e. transverse) to the rolling direction. Tensile tests were carried out at room temperature under a constant cross-head speed (at an initial strain rate of $1 \times 10^{-3}\ s^{-1}$).

Optical photographs of the as-received sample and those obtained after ECAR for one and three passes are shown in Figure 1(a)–(c). The microstructure of the as-received sheet with a grain size of 22.8 m shows a few twins and deformation bands in some grains. During the first pass by ECAR, extensive twinning took place. Grains were coarsened rather than refined ($d = 34.3$ m) due to rapid grain growth during the sample preheating and the absence of recrystallization during the ECAR process. After three passes by ECAR, grains were refined as a result of repeated rolling, but only slightly ($d = 21.5$ m). Rapid grain growth during the repeated heating between the rolling passes is considered to have nearly canceled the grain refining effect by ECAR. Many twins are also seen in the three-pass ECAR sample. As twinning is known to become active in polycrystalline magnesium at temperatures below 473 K [10], the extensive twinning during the current ECAR process despite the sample preheating at 623 K is mostly likely attributed to the fast rate of heat dissipation from the sheet to the cold ECAR mould.

The microstructures of the one- and three-pass ECAR samples after 15%, 30% and 70% thickness reductions by HRDSR are shown in Figure 1(d)–(i). It is obvious that the degree of grain refinement and the homogeneity of grain-size distribution are increased with increasing thickness reduction by HRDSR. The variation in area fraction as a function of grain size for the deformed samples is shown in Figure 2, together with information about their mean grain sizes. The population of fine grains increases with increasing thickness reduction as a result of the successive breaking-up of coarse grains into finer grains by dynamic recrystallization; a fully recrystallized microstructure is obtained after the 70% reduction. Microstructural morphologies and grain sizes observed at the top surface, center and bottom surface layers were similar in each of the one- and three-pass ECAR samples after the 70% reduction, indicating that a high degree of microstructural homogeneity was achieved across the sheet thickness. The grain sizes of the one- and three-pass ECAR samples after the 70% reduction were 1.2 vs. 2.3 μm, respectively, the former exhibiting a more homogeneous grain-size distribution. Twinning was rarely observed in both of the microstructures since the rolling temperature was as high as 473 K and deformation twinning is known

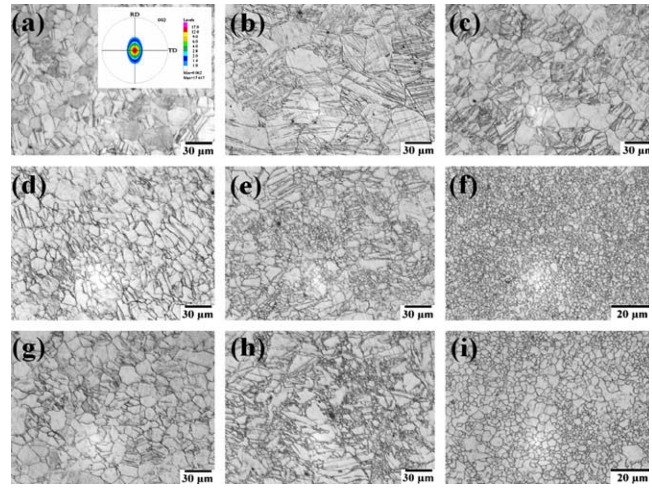

Figure 1. Microstructures of (a) the as-received sample and the ECAR samples after (b) one pass and (c) three passes. The microstructures of the one-pass ECAR sample after (d) 15%, (e) 30% and (f) 70% thickness reductions by HRDSR and those of the three-pass ECAR samples after (g) 15%, (h) 30% and (i) 70% thickness reductions by HRDSR. For all the materials, the rolling direction is from left to right. The (0002) pole figure of the as-received sample is shown in the insert in (a).

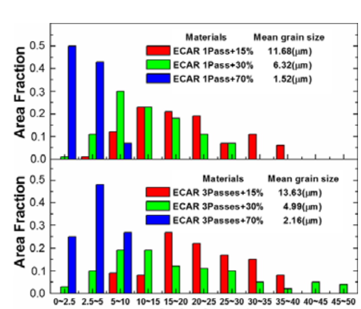

Figure 2. The variation of area fraction as a function of grain size for the rolled alloys.