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Effects of thickness reduction per pass on microstructure and texture of Mg–3Al–1Zn alloy sheet processed by differential speed rolling

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The influence of reduction per pass over the range of 9–63% on the microstructure and texture of Mg–3Al–1Zn magnesium alloy sheets processed by differential speed rolling at the same total reduction of 63% have been investigated. With increasing reduction per pass, the number of unidirectional shear bands increases, resulting in a more homogeneous microstructure and a weaker basal texture at mid-layer. The inclination direction of the basal pole with respect to the rolling direction depends on the reduction per pass.

Keywords: Magnesium alloy; Differential speed rolling; Rolling reduction ratio; Microstructure; Texture

Magnesium (Mg) wrought alloys have great potential as lightweight structural materials especially in automotive applications [1]. However, conventionally hot-rolled Mg alloy sheets generally exhibit a strong basal texture, which results in a very poor cold-formability and thus their applications are extremely limited [2]. The ductility of Mg alloys is strongly affected by the texture [3]. The tensile elongation can be significantly improved using equal channel angular pressing (ECAP), which results in a tilted basal pole with *c*-axes inclined at nearly 45° with respect to the extrusion direction and thus a favored crystalline orientation for basal slip [3,4]. Also, the formability of the Mg alloy sheets can be improved by inclination of basal pole and reduction of basal texture intensity [5–7]. In general, the texture of as-rolled Mg alloy sheet is weakly influenced by subsequent heat treatment; it is therefore important to control the rolling texture in order to achieve a superior formability. Differential speed rolling (DSR) is a process carried out at different rotation speeds for upper and lower rolls so that intense shear deformation can be introduced throughout the sheet thickness, thus leading to a different texture from that obtained by normal symmetric rolling [8]. Recently, it has been reported that DSR is effective for improving tensile elongation [9–11] and press formability [7] of Mg alloy sheets. For normal symmetric rolling, the effects of thickness reduction ratio on microstructure and texture have been investigated using materials with different initial textures, e.g. random crystalline orientation and strong basal texture [12–16]. However, an understanding of the effects of the reduction per pass on the Mg alloy sheet during the DSR process is still lacking. In particular, the relationship between the reduction per pass and the inclination of the basal pole is still not clear. In this study, DSR was carried out on Mg–3Al–1Zn (AZ31) alloy in order to investigate the influences of the reduction per pass on microstructure and texture of as-rolled sheet.

The starting billets were cut from the commercial hot-extruded AZ31 (Mg–3.10Zn–1.06Al–0.35Mn in mass%) alloy plate with a thickness of 4 mm, and then the starting billets were annealed at 723 K for 24 h in an argon atmosphere to improve their rollability. The annealed plate consisted of equiaxed grains with a grain size of 54 μm. The hot-extruded plate was used for the DSR process because it generally exhibits a better workability

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compared with the as-cast Mg alloy block due to its much smaller grain size. The DSR process was carried out at a rotation speed ratio of 1.167 without lubrication on sheet and roll surfaces and the rolling direction was parallel to the extrusion direction (ED). The billet temperature was 573 K and both rolls were heated to the same temperature. The billet temperature was monitored by a K-type thermocouple contacting the billet during heating in a pre-heated furnace. The billet was rolled immediately followed by air cooling when the temperature reached 573 K. The billet was reheated to 573 K again between two passes. The heating time for one run was less than 10 min. The sheets were rotated and reversed after each pass so that the shear strain was introduced unidirectionally. The billets were rolled from 4 to 1.5 mm in thickness with a same total reduction of 63% by a single pass, 2, 4, 6, 8 and 10 passes, which corresponded to 63%, 39%, 22%, 15%, 12% and 9% reduction per pass, respectively. The same total reduction was conducted because this is generally important when designing a rolling pass schedule for rolling a plate to a desirable end thickness in practical production.

The X-ray texture analysis was performed by the Schulz reflection method at α-angles ranging from 15° to 90° using a Rigaku RINT2000. For the DSR-processed sheets, the pole figures were measured at the near-surface (0.1 mm in thickness was removed from the surface) and the mid-layer with an observation direction from the high-speed roll side at the last rolling pass. Electron backscattered diffraction (EBSD) analyses were carried out at a step size of 1 μm using a JEOL JSM-5910 scanning electron microscope. Hereafter, RD, TD and ND denote the rolling direction, the transverse direction and the normal direction, respectively.

The hot-extruded and annealed plate exhibits a strong basal texture with a spread of (0002) orientation in the TD. There is a significant through-thickness texture gradient. The near-surface (0.2 mm in thickness was removed from the surface) exhibits a much larger basal texture intensity compared with the mid-layer (35.0 vs. 11.7). In addition, the spread of (0002) orientation in the TD is more notable for the mid-layer.

Figure 1 reveals the microstructures of the sheets DSR-processed at 9%, 12%, 15%, 22% and 63% reduction per pass. With increasing reduction per pass, the amount of the unidirectional shear bands with a smaller grain size increases, resulting in a more homogeneous microstructure, and the shear bands are nearly indistinguishable for the sheets rolled at the reduction per pass larger than 22%. For the large reduction single pass of 63%, some coarse grains are elongated along the RD due to plastic deformation without the occurrence of recrystallization. The deformation twins traversing the elongated grains are also evident. These twins were confirmed to be $\{10\bar{1}2\}$ extension twin by the EBSD.

The grain sizes of the sheets rolled at different thickness reduction per pass are summarized in Table 1. The grain sizes of the sheets rolled at 9%, 12%, 15%, 22%, 39% and 63% reduction per pass are 12, 12, 10, 10, 9 and 11 μm, which are remarkably reduced from the initial large grain size of 54 μm by the DSR process. The grain size decreases with increasing reduction per pass and reaches a minimum value of 9 μm at 39% reduction

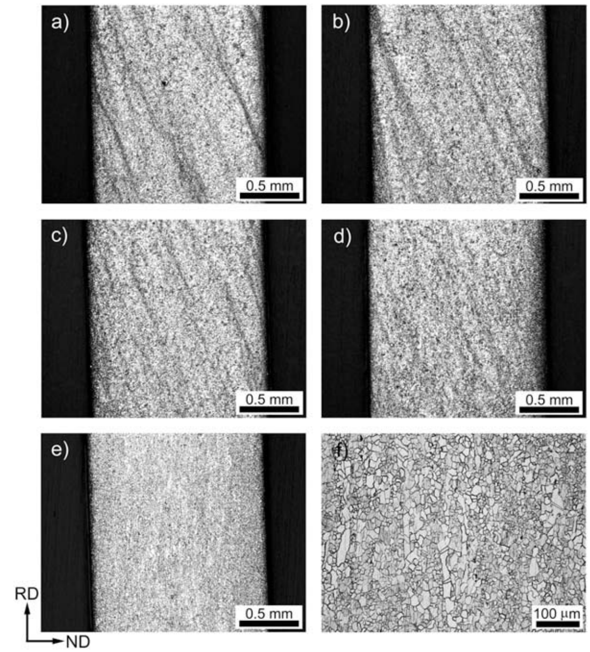

Figure 1. Optical micrographs taken in the RD–ND plane of the sheets DSR-processed at (a) 9%, (b) 12%, (c) 15%, (d) 22%, (e) 63% reduction per pass and (f) magnified section of the sheets DSR-processed at 63% reduction per pass. The right sides of the sheets contacted the high-speed roll at the last rolling pass.

Table 1. Grain sizes of the sheets rolled at different thickness reductions per pass.

Reduction per pass (%)	9	12	15	22	39	63
Grain size (μm)	12	12	10	10	9	11

per pass and then increases again to 11 μm for the largest reduction per pass of 63% (single rolling pass). The smallest grain size for the former case is due to the increase in the amount of the shear bands with a smaller grain size and the decrease in the amount of the elongated grains. In contrast, the larger grain size for the latter case is due to the elongated coarse grains without recrystallization. The amount of the elongated grains decreases with decreasing reduction per pass, i.e. increasing the total rolling pass number. This may result from dynamic recrystallization due to strain accumulation and/or static recrystallization during the reheating between passes.

Figure 2 shows the (0002) pole figures of the sheets DSR-processed at 9% and 39% reduction per pass. The reduction per pass strongly affects the rolling texture including the characteristics of the inclination direction and angle of the basal pole, the texture intensity and the orientation distribution. For the mid-layer, a remarkable spread of the (0002) orientation in the TD exists in the sheet rolled at a large reduction per pass, i.e. a small total rolling pass number, and it disappears with increasing the total rolling pass number. The spread of the (0002) orientation in the TD may be due to the initial extrusion texture. The changes in the basal texture intensity and the inclination angle of the basal pole are summarized in Figure 3. After the DSR