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Improved ductility of Mg–Zn–Ce alloy by hot pack-rolling

T. Wu [a], L. Jin [a,*], W.X. Wu [a], L. Gao [b], J. Wang [b], Z.Y. Zhang [a], J. Dong [a]

[a] National Engineering Research Center of Light Alloy Net Forming, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] General Motors China Science Lab, Shanghai 201206, PR China

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ABSTRACT

The microstructure and mechanical properties of Mg–2%Zn–0.5%Ce (ZE20) sheets by hot pack-rolling was investigated. The results showed that pack-rolled ZE20 sheets exhibited a fine recrystallized microstructure, weak texture, good ductility and a low *r*-value due to the reduction of heat losses by pack-rolling processing. Annealing treatment at the given temperature for conventional-rolled specimens was slightly effective for the improvement of ductility, however, resulting in strong basal texture. More randomized texture and weaker anisotropy were obtained when rolled at 723 K, which might indicate that the temperature-strain parameters in pack-rolling were in a suitable window for solute drag effect and texture randomization in Mg–RE alloy.

1. Introduction

Magnesium and its alloys have attracted great attention in recent years and are proved to be promising materials in the automobile and aerospace areas [1,2]. Unfortunately, due to the hexagonal structure and lack of sufficient slip systems, magnesium and its alloys exhibit poor formability at room temperature. During conventional rolling process, the vast majority of grains are oriented such that their basal planes are close to the sheet plane. Such textures place most grains in an orientation where it is difficult to deform and result in high flow stress, modest work hardening and, therefore, low values of uniform elongation.

Previous studies have shown that texture optimization and grain refinement are the two methods recommended to improve the formability of magnesium alloys at room temperature. However, it is still a challenge to weaken the texture of Mg sheet. A lot of studies have been done on how to weaken basal textures in Mg alloys so as to enhance their formability. Huang et al. [3] have done researches on AZ31 alloy sheet high temperature (at 798 K) rolling, and reported that dynamic recrystallization (DRX) occurred at high temperatures, which lead to grain refinement and weakened split-texture in magnesium alloys. In addition, previous study has shown that AZ31 alloy sheets rolled at 673 K performed a better ductility and weaker texture than those rolled at 573 K, which is attributed to the different deformation behaviors as contraction twinning and double twinning [4].

On the other hand, rare earth (RE) addition, such as Gd, Y, La, Ce and Nd [5–8], were reported to have weakened the texture of Mg extrusion or rolling sheet and benefit for the improvement of ductility. Among them, Ce is a commonly used RE element because of the relatively low cost and large atom size. In Mackenzie's work [7], they reported that addition of Ce in Mg–Zn alloys led to texture randomization in the condition of recrystallization. Similar results have also been reported by Chino [9]. They obtained a weaker texture and a higher tensile elongation together with better stretch formability due to the addition of Ce in pure magnesium. One suggested reason is that Ce has a potential to lower the critical resolved shear stress (CRSS) of non-basal slips and then broaden the *c*-axis along the normal direction of the sheet [9].

Above results suggest that the microstructure evolution is severely dependent on the temperature and alloy composition. However, the mechanism of texture evolution, anisotropy and ductility improvement at high temperatures is still indistinct. As the temperature loss during hot rolling is inevitable, the actual temperature is much lower than the selected one. Pack-rolling is initially developed for difficult-to-roll materials as titanium alloys, and the cover used is Ti–Al alloys because they are with similar characters but the cover is softer and easier to deform [10–13]. Other researchers [13,14] have used stainless steel as cover for Ti-based alloys and Ni-based alloys and Al as cover for Cu during rolling. In their researches, pack-rolling is proved to be very effective for temperature saving. However, this process is seldom used for magnesium alloys. In this study, a pack-rolling processing with Al was utilized to optimize the microstructure and improve the ductility of magnesium alloy sheets, because Al is a relatively low-cost metal and easy to deform. Besides, the developing of

* Corresponding author. Tel.: +86 213 420 3052; fax: +86 213 420 2794.
E-mail address: J_jinli@sjtu.edu.cn (L. Jin).

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Mg–Ce series alloys with good formability has a great industrial prospect. In this study, Mg–Zn–Ce alloy was used to investigate the effect of pack-rolling processing on the grain refinement, texture weakening and deformation behavior.

2. Experimental procedures

The material used in this study was Mg–2%Zn–0.5%Ce (ZE20) alloy by continuous casting followed by homogenization at 823 K for 8 h, and the billet was machined to 150 mm × 70 mm × 10 mm. Before rolling, ZE20 alloy sheets were packed with 6063 Al and billets without Al-packing were also prepared as comparison, which were referred as conventional rolled sheets. Deformation parameters for all the specimens were listed in Table 1. The initial billets were heated in the furnace at 673 K and 723 K respectively for 60 min. Between two consecutive rolling passes, the billets were heat-preserved for 15 min at the given temperature to maintain the rolling temperature. All ZE20 alloy sheets were rolled for 8 passes to a thickness of approximately 2.5 mm. After rolling, conventional-rolled billet was annealed at the given temperature to obtain a homogenous microstructure and to investigate the effect of pack-rolling by ruling out the influence of homogeneous microstructure. The pack-rolled ZE20 sheets were separated from the Al-pack for microstructure observation and mechanical properties testing.

Microstructure characterization was done by optical microscope (OM) and electron backscattered diffraction (EBSD). Tension specimens with 10 mm gauge length were pulled to failure on a Zwick/Roell tester, where the angle between the tensile direction and rolling direction (RD) were 0°, 45° and 90°, respectively. The stretching rate was 1 mm/min. For *r*-value testing, the specimens were strained to a uniform elongation of 9%. The Lankford values (*r*-values) were calculated according to Eqs. (1) and (2):

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln w/w_0}{\ln t/t_0} \tag{1}$$

$$\bar{r} = \frac{r_0 + r_{90} + 2r_{45}}{4} \tag{2}$$

where w_0 was the initial width and t_0 was the initial thickness, w was the width and t was the thickness after tensile test.

3. Results and discussion

Fig. 1a and b shows the microstructures of the as-cast and homogenized ZE20 alloy, respectively. The initial grain size is approximately 180 μm. It can be observed that the number of Mg–Zn–Ce particles is notably decreased after the solid solution treatment. Fig. 1c illustrates the general view of pack-rolling, which shows that Al-packs act as heat-preservers to avoid heat losses during hot rolling. Also, the gap between the pack and the workpiece suggests Al-pack undergoes more deformation than the workpiece during the rolling process. The macrograph of the sheets after rolling is shown in Fig. 2. As can be seen, pack-rolled sheet shows a metallic luster appearance and is free of cracks. However, obvious surface oxidation and cracks can be seen from the sheet by conventional rolling. It indicates that Al-packs can not only act as good heat-preservers but also help prevent edge cracking and surface oxidation.

Table 1
Pre-processing conditions and rolling temperature for all specimens.

Sample no.	Al-packing	Rolling temperature (K)	After deformation processing
S1	No	673	–
S2	No	673	Annealed at 673 K for 30 min
S3	Yes	673	–
S4	Yes	723	–

The inverse pole figure (IPF) maps of conventional-rolled sheets are shown in Fig. 3 and the observed plane is the rolling direction (RD)–transverse direction (TD) plane. As is shown in Fig. 3a, after conventional rolling, the specimen exhibits an inhomogeneous microstructure with twinning, large deformed grains and small recrystallized grains. The fraction of recrystallization is low and these recrystallization grains might result from the dislocation rearrangements in the previous deformation according to Jin's [15] research. In the deformed grains lots of low angle grain boundaries (LAGB, white line) or sub-grain boundaries are observed. Fig. 3b shows the amplified IPF map and grain map in the black box of Fig. 3a. The twins are defined as {−1011}–{10–12} double twins, {−1011} contract twins and {10–12} extension twins, which is consistent with the research work done before by Jiang [16] and Park [17]. From the grain orientation in Fig. 3b, it can be seen that basal planes of most grains are mainly oriented parallel to the sheet plane, which indicates a strong basal texture.

The heterogeneous microstructure obtained by conventional rolling can be replaced by fully recrystallized grains after annealing, as shown in Fig. 4a. However, grain growth is obvious during annealing and the average grain size is approximately 43 μm. Unlike conventional rolling processing, pack-rolled ZE20 sheets deformed at 673 K and 723 K show more homogeneous microstructures with fully recrystallization, as shown in Fig. 4b and c, respectively. The grain size for the sheet rolled at 673 K is about 7.3 μm and for that rolled at 723 K is 9.5 μm. These results suggest that hot pack-rolling could lead to more homogeneous microstructures as well as fine grains, which might result from the higher deformation temperature via Al-packing treatment. The (0002) pole figures of the rolled and annealed ZE20 sheets are also shown in Fig. 4. Conventional-rolled and annealed specimen has shown a strong basal texture with its *c*-axis parallel to the normal direction (ND) of the rolling plane and the maximum texture intensity is 18.38. However, the pack-rolled sheets show weaker basal textures and a split from basal planes as in Fig. 4d and f. The results suggest that the texture evolution in magnesium alloys is strongly dependent on the processing parameters.

Fig. 5 illustrates the tensile properties of rolled sheets along three directions: rolling direction (RD), 45° to RD and 90° to RD (TD). Conventional rolling at 673 K exhibits the highest yield strength (199.2 MPa along RD), which might result from the strong texture and inhomogeneous microstructure. However, its ductility is inevitably low, with an elongation of only 6.0% along RD. After annealing at 673 K for 30 min, the uniform elongation of conventional-rolled sheet increases to 13.8% along RD but this value is still relatively low. However, sheets pack-rolled at 673 K exhibit lower yield strength and ultimate tensile strength, while the tensile elongation in the rolling direction (RD) is 28.23%, which is about twice of that for the specimen conventional-rolled and annealed. Pack-rolling at 723 K results in the best tensile properties, with a uniform elongation of 33.4% along RD. This indicates that tensile properties of the annealed specimen are much poorer than that of pack-rolled sheets. Though annealing treatment slightly enhances the uniform elongation of conventional-rolled sheets, pack-rolling could improve the ductility of rolled sheets to a large extent. It can be seen from Fig. 5 that 673 K pack-rolling still exhibits an obvious anisotropy when strained along RD, TD and 45° to RD. Comparably, sheets pack-rolled at 723 K show much weaker anisotropy in ductility and lower yield stress.

In order to evaluate the anisotropic property of the deformed specimens, Lankford values (*r*-values) of sheets were measured in