Rev. Adv. Mater. Sci. 33 (2013) 153-156

GRAIN REFINEMENT IN THE SURFACE LAYER OF AZ31 Mg ALLOY SHEET PROCESSED BY CYCLIC BENDING

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Received: October 17, 2011

Abstract. Grain refinement in the sheets of magnesium alloy AZ31 was studied by means of cyclic in-plane bending at 423K. The deformed and subsequent annealed microstructures were investigated by optical and SEM/EBSD metallographic observation. Deformation twins are frequently formed in the original grain interiors. Bending induces a gradient structure with high-density twins in the surface layer and, in contrast, lower density ones in the center. The grain size in the surface layer is refined steadily with increasing strain passes due to operation of twin dynamic recrystallization based on twin intersections. After bending of 6 passes at 423K followed by a subsequent annealing at 523K, the average grain size in the surface layer was reduced to about 10 μm from the original size of 46 μm. In particularly, the relative intensity of the strong texture developed in the sheets was severely weakened by repeated bending.

1. INTRODUCTION

Magnesium alloy sheets have generally poor plasticity and stamping formability at ambient temperature due to a lack of sufficient number of slip systems associated with hexagonal close-packed (hcp) crystal structure and also a strong basal texture developed in rolled sheets [1,2]. Most grains in the sheets are almost oriented such that their basal planes are roughly parallel to the sheet plane. Mg sheets with such a texture are hard to be further deformed, resulting in low ductility. It is found [3-5] that Mg alloy polycrystals with any random textures result in higher strain-hardening rates and then promotes a stable plastic flow as well as improved formability. It is well known that grain refinement taking place in Mg alloys could improve not only the plastic workability, but also the strength at ambient temperature [6]. For more extended application of Mg sheets, therefore, it is necessary to refine the initial grains and also randomize the texture to improve the formability. Recently, some special deformation techniques have been invented and applied to Mg alloy sheets to develop the finer-grained structures with random texture. Song *et al.* [7] have improved the mechanical ductility of AZ31B Mg alloy sheets at ambient temperature by repeated unidirectional bending (RUB). Because most the c-axis was enforced to turn from the normal direction towards the rolling direction by RUB. A strong texture, however, still remained after RUB followed by subsequent annealing. Yang and Ghosh [8] carried out by using alternate biaxial reverse corrugation on Mg alloys at temperatures ranging from 523K to 443K and obtained a nearly uniform ultrafine microstructure with a grain size of 1.4 μm.

It is also known [9] that twinning often plays an important role on deformation and structural changes during deformation of Mg and its alloys at low temperature. Abrupt changes of matrix orientation due to twinning would modify the texture and give rise to any activation of various slip systems. In the

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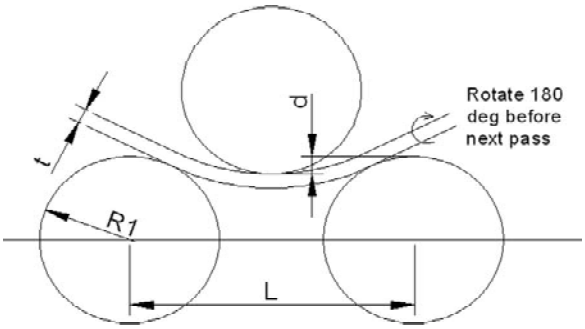

Fig. 1. The Cyclic in-plane bending device used in experiment.

present study, bidirectional cyclic bending followed by annealing was applied to AZ31 Mg alloy sheets, because this process may be considerably randomized the original textures. Optical microcopy and electron backscatter diffraction pattern technique were used for microstructural observations.

2. EXPERIMENTAL METHOD

The material used was a hot-rolled AZ31 Mg alloy sheet with thickness of 1.6 mm which had the following chemical composition (in mass %): Al 2.68, Zn 0.75, Mn 0.68, Cu 0.001, Si 0.003, Fe 0.003, and balance Mg. The sheet samples were annealed at 723K for 30 min and then cooled in air, leading to an equiaxed grain structure with an average size of 46 mm (see Fig. 2a).

The samples were subjected to cyclic in-plane bending with a temperature of 423K. A pass strain was 0.2 evolved in the surface layer. The device specially designed and constructed is illustrated in Fig. 1. The strain of the surface layer per pass is calculated by Eq. 1 [10].

$$\varepsilon = \frac{4}{\sqrt{3}} \ln\left(1 + \frac{1}{2R/t + 1}\right), \tag{1}$$

where R is the arc radius of the concave of the bended sample and t is the thickness of the sheet. Since an asymmetric stress state was produced on the surfaces in both sides, the tests were carried out alternately to keep the symmetry of strain. The concave at the first pass was defined as upper surface and, in contrast, the convex was defined as lower surface. After deformation to a selected number of passes, the samples were annealed at 523K for 6×10^2-10^3 s. Each sample was mechanically and electrolytically polished and then etched in a solution of 6% picric acid and 94% methanol on the ND-RD plane. Microstructures were examined by using optical microscopy and scanning electron microscopy (SEM) incorporating an orientation imaging microscopy (OIM) system.

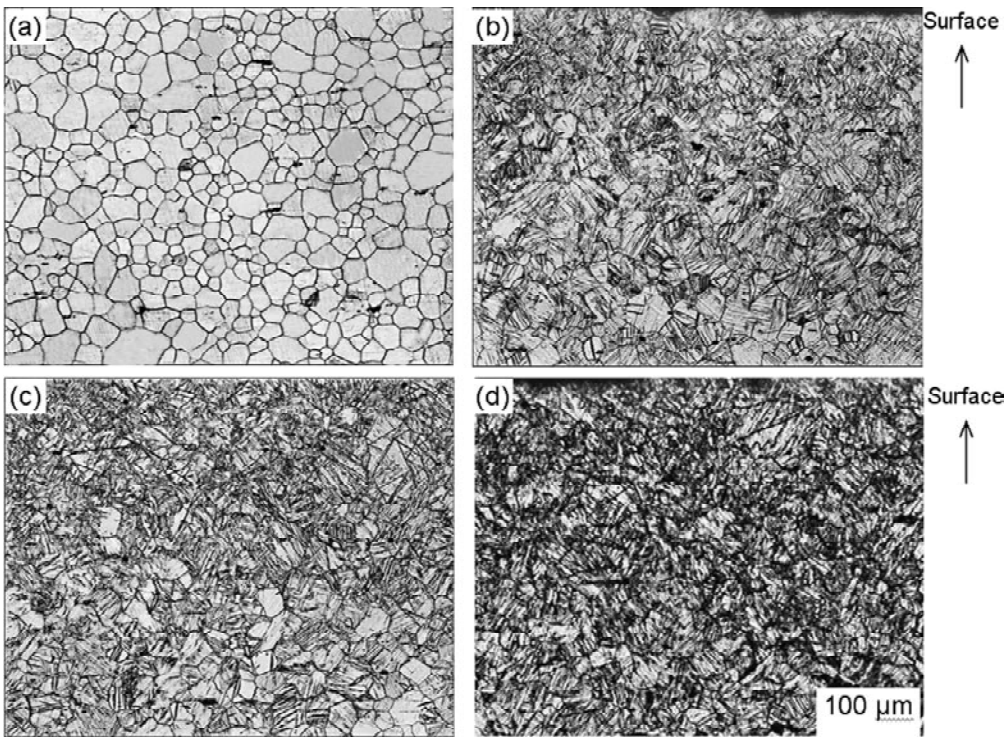

Fig. 2. Microstructures of AZ31 Mg alloy sheet (a) before deformation, and (b) to (d) after deformation at 423K. (b) 4 passes, (c) 6 passes, and (d) 8 passes.

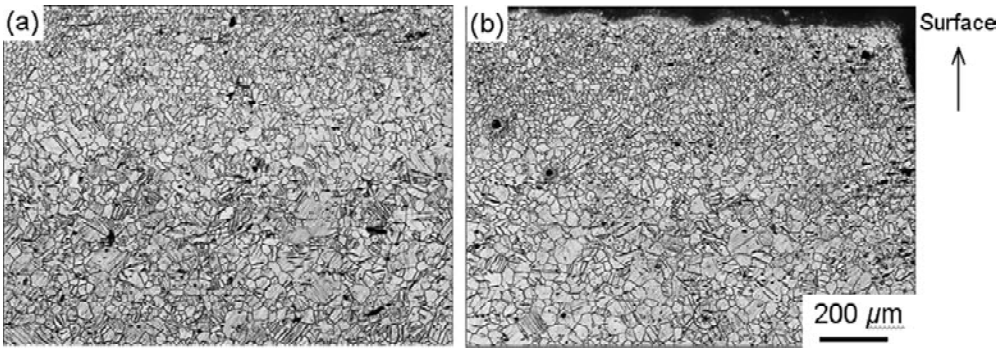

Fig. 3. Microstructures after 6-passes bending at 423K followed by annealing at 523K for (a) 6×10^2 s and (b) 10^3 s.

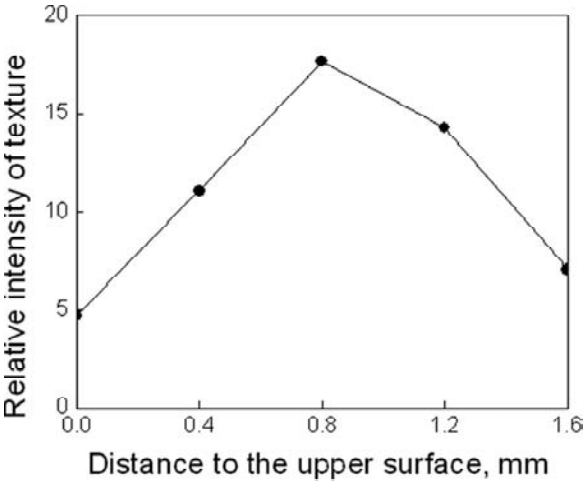

Fig. 4. Change in relative intensity of texture with distance after 6-passes bending followed by annealing at 523K for 10^3 s.

3. RESULTS AND DISCUSSION

3.1. Microstructural changes with cyclic bending

Fig. 2 shows the microstructures in the upper surface layer of the Mg sheet deformed at 423K to different passes. The microstructures evolved in the surface and the middle layer of the sheet corresponds to those in the upper and lower side in each figure. After 4-passes cyclic bending, high density twins are evolved in grain interiors, as show in Fig. 2b. It is clearly seen that the density of twins evolved decreases with distance from the surface, i.e. the upper side of Fig. 2b. With further increase in bending pass, twins are more frequently formed and the initial grain boundaries become more and more indistinct, as show in Figs. 2c and 2d. Ultrafine grained regions are locally extended at near the surface and their volume fraction increases continuously with cyclic bending. The average grain size of the surface layer is refined steadily with increasing of strain passes. The rolled sheet of AZ31 Mg alloy had a strong basal texture, and so non-basal slip modes cannot be activated effectively at 423K. Twinning would perform as one of the most important deformation mode at low temperature [9]. As *c*-axis compression and tensile stress are inflicted on the convex and the concave respectively at each deformation pass, compression and {10-12} tensile twins are formed alternatively on each side. With increase in deformation pass, both side of the sheet will bear an alternate compression and tensile stress. Then compression and tensile twins alternately formed can lead to twinning intersections and double twinning in the original grain interiors [9]. As high stresses concentrated evolve in the regions of intersections, twin dynamic recrystallization may operate and then result in formation of ultrafine grains.

3.2. Microstructural evolution during annealing

Fig. 3 shows the microstructures evolved after annealing at 523K following 6-passes cyclic bending at 423K. It is seen that fine grains are fully developed throughout the surface layer with an average grain size of 10 μm after annealing for 6×10^2 s, while twinning structures are still remained in the middle layer. Such a microstructure does not change by increasing annealing time to 10^3 s, as show in Fig. 3b.

Fig. 4 shows change in the relative intensity of texture along ND direction with distance from the upper surface after annealing at 523K for 10^3 s. The relative intensity of texture shows a maximum at near the center, i.e. 0.8 mm, and changes with a negative gradient as the grain size from the surfaces to the middle layer. The texture in both the surface layers is clearly weakened to less than one third of the middle layer. It is concluded that the present cyclic bending technique can severely weaken the original basal textures especially in the surface layers.

Li *et al.* [11] studied static recrystallization in AZ31 magnesium alloy containing tension twins and found that new grains nucleate preferentially at the intersections of tension twin variants and/or the intersections between tension and compression twins. Then their orientations were relative random and are strongly scattered from those of original tension twins or compression twins. Since the surface layers are produced higher strain than the middle layer, more twins and denser twin intersections would be observed there. Recrystallized grains can rapidly nucleate in the intersections of twins in the surface layers. Furthermore, ultrafine grains locally formed in deformation process can perform as new nucleuses and then accelerate the recrystallization progress. However, the middle layer would remain most of the twin structures for a lack of activated energy. It should be added that twinning often induce grain orientation rotation, for example, the {10-12} tension twinning and {10-11} and {10-13} compression twinning would cause a misorientation between the matrix of 86°, 56° and 64° for a <1-210> rotation axis respectively. The original texture would be modified severely after deformation. Then in the followed annealing process, the new grains with more random orientations results in severely texture weakening.

4. CONCLUSION

The microstructure and texture development taking place during cyclic in-plane bending at 423K and subsequent annealing at 523K were studied by using Mg alloy AZ31 sheet. The main results obtained are summarized as follows.

1) Deformation twins are rapidly formed in initial grain interiors by bending, which induce a gradient structure with high-density twins in the surface layer and low-density twins in the middle layer. Grain refinement based on twin intersections gradually occurs and lead the grain size of the surface layer to refine steadily with increasing strain passes.

2) After 6 passes cyclic bending followed by annealing for 10^3 s, the grain size of 46 μm in the surface layer is reduced to about 10 μm. At the same time, the relative intensity of the original texture is severely weakened.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from the National Science Foundation of China (Grant No. 51071182) and National Key Basic Research Program of China (Grant No 2013CB 632204).

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