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ARTICLE

Microstructure and Mechanical Property Development in a Hot-rolled and Annealed Mg-5Li-1Al Alloy Sheet

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Abstract: Mg-5Li-1Al magnesium alloy sheets processed by hot rolling were annealed at 150 and 300 °C for 30 min. The microstructure, mechanical properties, and texture of the rolled and annealed Mg-5Li-1Al alloy sheet were investigated. The plastic deformation mechanism was also discussed. The results show that the annealed sheet possesses weak basal texture and homogenous recrystallized structure with grain size of ~15 μm. Increasing annealing temperature results in an increase in tensile elongation and a decrease in tensile strength, yield strength and yield ratio, which generally favor the improvement of sheet formability. The rolled LA51 sheet after annealing at 300 °C exhibits improved mechanical properties due to Li addition and high annealing temperature.

Key words: microstructure; mechanical property; Mg-Li alloy; hot-rolling; annealing

Due to their low density and high specific strength, magnesium alloys have been highlighted as potential candidates for eco-friendly materials[1-4]. However, the poor ductility and sheet formability at ambient temperature due to the hexagonal close-packed structure of Mg alloys have severely restricted their applications. Nowadays, many researchers have focused on the enhancement of the room-temperature formability of Mg alloy sheets by means of grain refinement and texture control[5-7]. It is well known that lithium additions in Mg alloys can improve the room temperature formability[8]. This improvement is, in general, attributed to the weakening of basal texture and the activation of non-basal slip modes. It has been shown that a little addition of lithium (Li) can lower the c/a ratio of the Mg crystal structure and efficiently activate prismatic and pyramidal slip systems by reducing the critical resolved shear stress (CRSS), thus improving the formability of Mg alloys[9,10]. Moreover, the addition of Li can transform the crystal structure of Mg alloy from hexagonal close packed (hcp) to body centered cubic (bcc) with more slip systems. Above ~5.5 wt% Li addition, the hcp Mg-Li alloy becomes a duplex alloy with both hcp α-Mg and bcc β-Li phases existing simultaneously; while above ~11.5 wt%, the alloy is totally bcc[11,12]. The bcc phase displays much greater ductility than the hcp counterparts when deforming in Mg-Li alloys[13,14]. However, the binary Mg-Li alloys do not intrinsically demonstrate the necessary strength for their engineering applications[15]. It has been found that Al is one of the potential alloying elements due to its capacity to strengthen Mg alloys. Strengthening Mg-Li alloys with Al addition is commonly through solid solution and/or intermetallic compound reinforcements[16,17]. Deformation processing, such as forging, extrusion, and rolling, are also carried out to further strengthen Mg-Li alloys[18-20].

Thus, it is essential to understand the deformation mode transitions for developing hcp structural Mg-Li alloys with a good combination of strength and ductility. The focus of the present investigation is only on the alloy possessing hcp α-Mg phase with the addition of 5 wt% Li and 1 wt% Al. The microstructure, mechanical properties, and texture of traditional rolled Mg-5Li-1Al (LA51) alloy sheet were investigated. The plastic deformation mechanism was also discussed.

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1 Experiment

The initial material used in the present work was extruded LA51 alloy (Mg-5Li-1Al, wt%) billet with a thickness of 2.0 mm. The extruded billet was preheated to 300 °C, and then rolled to 1.0 mm in thickness by only one pass with thickness reduction of 50%. The rotation speed of both rolls was 10 $m\cdot min^{-1}$. Finally, the rolled sheets were annealed at 150 °C and 300 °C for 30 min.

Microstructural characterization was performed on specimens in the as-rolled, and the rolled and annealed conditions. Optical micrographs of the rolled sheets are observed in the plane containing the rolling direction (RD) and normal direction (ND); and the RD is horizontal. For optical microscopy observation, specimens were cut, ground, polished, and finally etched for 1~5 s in the etchant (5 g picric acid, 10 mL acetic acid, and 95 mL ethyl alcohol). Electron backscattered diffraction (EBSD) was carried out on the annealed LA51 sheet. Following mechanical polishing, specimens were prepared for EBSD by electropolishing at 20 V for ~60 s at –15 °C in order to remove surface strain. EBSD data was acquired using HKL Channel 5 EBSD software. The annealed sheets were subsequently used for uniaxial tensile tests at room temperature, with an initial crosshead speed of 3 $mm\cdot min^{-1}$. The tensile tests were performed at the angles of 0° (RD), 45° and 90° (TD) between the tensile direction and the RD. The gauge length and width of the tensile specimens were 25 and 10 mm, respectively. The tensile tests were carried out on three samples for each direction.

2 Results and Discussion

2.1 Microstructure

Fig.1 shows the optical microstructures of the LA51 alloy sheets under different conditions. Fig.1a shows the microstructure of the extruded sheet. Due to dynamic recrystallization, the extruded sheet consists of homogeneous refined equiaxed grains. The average grain size is about 25 μm. Different from the extruded sheet, the as-rolled sheet exhibits a deformed microstructure characterized by large elongated grains, shear bands and high density of deformation twins (Fig.1b), and no apparent occurrence of dynamic recrystallization can be confirmed by optical microscopic observation. This transformation is attributed to the reorientation of most grains along the RD and the twinning evolution with deformation during rolling with large reduction perpass. Because of the relatively high rolling speed, rolling reduction, and cooling rate, no visible dynamic recrystallization is observed in the microstructure of the as-rolled sheet. It can be seen that annealing temperature has a profound effect on recrystallization. As shown in Fig.1c, the change in microstructure is still quite limited at the stage of annealing at 150 °C for 30 min (Fig.1c). A higher density of deformation twins form in the initial grains in hot-rolled sheet and annealed at 150 °C for 30 min, producing twin lamellae and/or grids (Fig.1b and Fig.1c). However, after full annealing at 300 °C for 30 min, static recrystallization extensively occurs and almost all of the deformed large grains change to small equiaxed grains in the sheet. The average grain size of the sheet annealed at 300 °C is 15 μm, which is effectively refined from the initial structure of the extruded sheet.

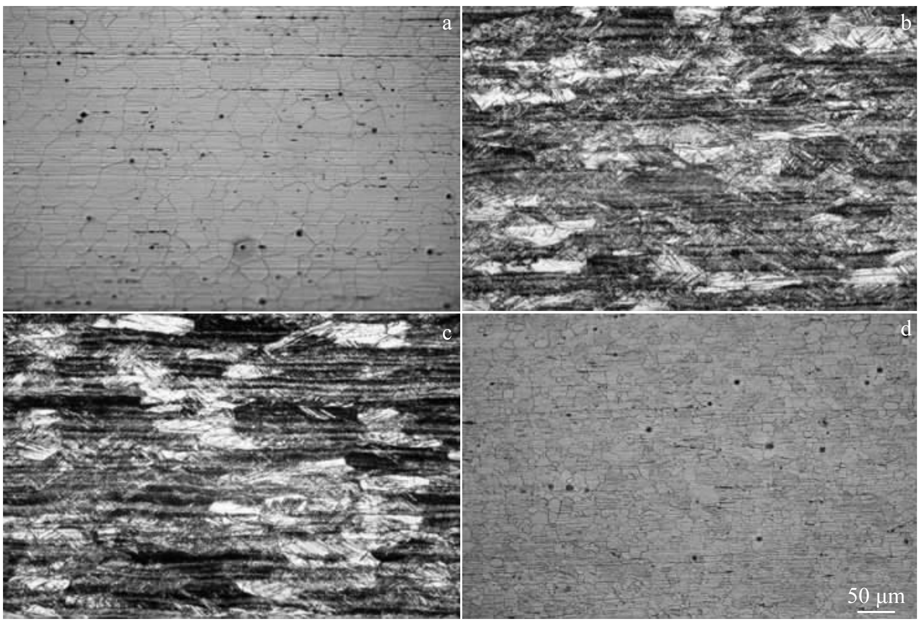

Fig.1 Optical microstructures of the sheet taken in the longitudinal section with horizontal ND/RD: (a) as-extruded condition, (b) as-rolled condition, and the same sheet rolled and annealed at 150 °C (c) and 300 °C (d) for 30 min

2.2 Mechanical properties

Fig.2 shows the nominal stress-strain curves. The tensile properties, including ultimate tensile strength (UTS), 0.2% proof stress (YS), yield ratio and fracture elongation (FE) in the tensile directions of RD, 45° and TD of the sheets annealed at 150 and 300 °C, are summarized in Table 1. The mechanical properties match well with the microstructure of the annealed specimens. The sheet annealed at 150 °C shows much high mechanical strength due to deformation twins and stress concentration. And the plane anisotropy of FE obviously appears in the sheet annealed at 150 °C. However, when annealing at a higher temperature of 300 °C, the LA51 sheet shows much smaller differences in tensile properties among the three different tensile directions. It can also be confirmed from the nearly lapped strain-stress curves (see Fig.2). The root cause of this is the weakened texture with a low basal texture intensity and the near-concentric orientation distribution as shown in Fig.3. The weak texture enhances the elongation, which leads to improved deformation capability during further processing. It is also well noted that the yield ratio decreases with the increasing of the annealing temperature. The low yield ratio (0.56) of the LA51 sheet annealed at 300 °C shows good deformation capability. It can be seen that the LA51 sheet annealed at 300 °C is optimal compared with the one annealed at 150 °C in terms of ductility. It was reported that the RE elements were found to be appropriate alloying elements to enhance Mg alloys. Here, for Mg-5Li-1Al alloy, the large elongation, as high as 35%, is obtained without other RE additions.

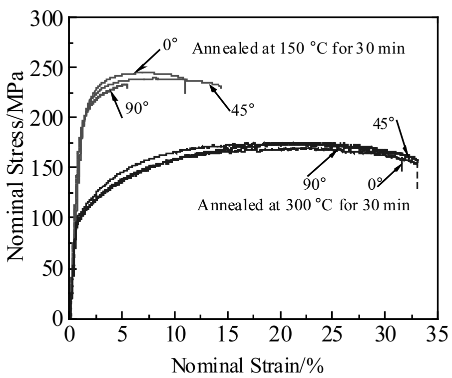

Fig.2 Nominal stress-strain curves in the tensile direction of RD, 45°, and TD of the sheets annealed at 150 and 300 °C for 30 min

Table 1 Mechanical properties of the as-annealed LA51 sheet

Annealing treatment	Orientation	UTS/ MPa	YS/ MPa	Yield ratio	FE/ %
150 °C/ 30 min	RD	243	196	0.81	10.83
	45°	238	197	0.83	15.77
	TD	235	183	0.78	8.15
300 °C/ 30 min	RD	175	105	0.60	35
	45°	168	101	0.60	38
	TD	174	97	0.56	37

2.3 Texture

In order to reveal recrystallization characteristics and the evolution of micro-texture, the EBSD analysis was carried out for the sample of the sheet annealed at 300 °C for 30 min. Fig.3 shows the inverse pole figure map and the (0001) pole figure, together with the distribution of grain boundary misorientation of the sheet after annealing at 300 °C. High angle grain boundaries (HAGB, with misorientation angles larger than 12°) are marked in black and low angle grain boundaries (LAGB, with misorientation angles smaller than 12°) are grey. The formation of LAGBs is clearly visible in the vicinity of the boundaries of the equiaxed grains. New grains with HAGBs also form in several areas near to the boundaries of the matrix grains. Moreover, they show no large deviations in orientation with respect to the matrix grain. The fraction of LAGB is lower than that of HAGB, which suggested that almost grains of the rolled LA51sheet are recrystallized after annealing at 300 °C. In addition, recovery in the interiors of these large initial grains may simultaneously occur with the progress of annealing, which further decreases dislocation densities and lowers stored energy in those regions[17,21,22]. The average grain size of the sheet annealed at 300 °C for 30 min is about 15 μm, measured by EBSD scan (Fig.3d).

The annealed sheet exhibits a weakened texture with the basal pole tilting in the RD at ~20°. The inclination of basal pole in the RD can constantly be observed for the different-speed rolled Mg alloy sheets due to the introduction of shear strain[5,18,20,23]. Besides the red basal grains with a majority fraction, some blue deformed grains with orientations close to (2110) orientation (denoted as prismatic grains hereafter) also exist, which leads to the formation of some spreading basal poles in the TD for the annealed sheet.

In general, grain boundaries, twins and shear bands are not only the places of stress concentrations, but also the favored regions for recrystallization. As is known that the solute Li can affect stacking fault energy of certain types of dislocations and therefore result in a change in relative CRSS for <*a*> and <*c*+*a*> dislocations, thus enhancing non-basal slips during deformation[23]. Meanwhile, benefiting from the enhanced non-basal slips, the Mg-Li alloy can deform more homogeneously and individual shear bands carry less strain than those in pure Mg.

The hot-rolled LA51 alloy contains high-density dislocations and a large amount of twins in the original grain interiors (as shown in Fig.1). The frequently intersecting twins can result in high strain concentrations around their intersections and grain boundaries, which can be regarded as the nuclei for static recrystallization[19]. Thus the optimal ductility and small anisotropy of the rolled and annealed LA51 sheet are resulted from the lithium addition, a large amount of deformation (50%)

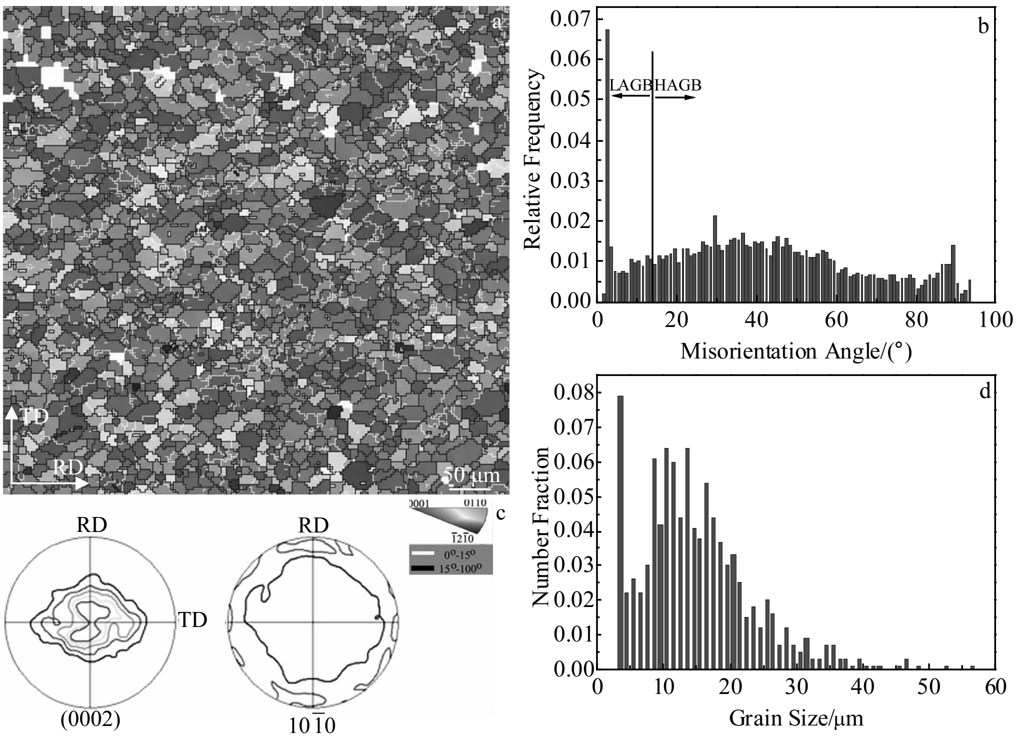

Fig.3 Inverse pole figure (IPF) map with horizontal RD (a), misorientation distribution profile (b), pole figure (c) and grain size distribution (d) of the sheet annealed at 300 °C for 30 min

and high annealing temperature.

3 Conclusions

1) The as-rolled LA51 sheet exhibits deformation microstructure regardless of the high rolling temperature. Static recrystallization occurs around the pre-existing grain boundaries, resulting in a weak basal texture with basal pole titling about 20^o during annealing at 300 °C.

2) The weakened texture leads to an excellent ductility compared to the low-temperature annealed one. The rolled and annealed LA51 sheet possesses higher ductility and much smaller plane anisotropy with a refined recrystallized microstructure.

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热轧及退火 Mg-5Li-1Al 板材的组织及力学性能演变

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摘　要：Mg-5Li-1Al 合金板材在热轧后分别经 150 和 300 ℃退火 30 min。研究了热轧及退火态 Mg-5Li-1Al 板材的微观组织、力学性能及织构，并且讨论了其塑性变形机制。结果显示，退火态板材显示出了弱的织构和均匀的再结晶组织，其晶粒尺寸约为 15 μm。随着退火温度的升高，合金板材的延伸率逐渐提升，而抗拉强度、屈服强度、屈强比减小，这些都对合金的成形性能非常有利。经 300 ℃退火 30 min 的合金板材表现出最好的力学性能，其原因在于 Li 元素的添加和退火温度的升高。

关键词：显微组织；力学性能；镁锂合金；热轧；退火

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