J Mater Sci (2009) 44:4593–4598
DOI 10.1007/s10853-009-3700-8

Stretch formability of Mn-free AZ31 Mg alloy rolled at high temperature (723 K)

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Received: 6 February 2009 / Accepted: 19 June 2009 / Published online: 7 July 2009

Abstract Stretch formability of Mn-free AZ31 Mg alloys rolled at 618 and 723 K was investigated at room temperature. The specimen rolled at 723 K showed superior stretch formability to that of the specimen rolled at 618 K. The (0002) plane texture of the specimen rolled at 723 K exhibited a low texture intensity compared with that of the specimen rolled at 618 K. It is suggested that the modification of basal texture by the high temperature rolling contributes to activation of basal slips, resulting in an enhancement of the stretch formability. Besides, it is suggested that coarse grain size of a Mn-free AZ31 alloy seems to enhance a stretch formability, because twins become easily generated during tensile loading.

Introduction

Mg alloys have the high potential for improving fuel efficiency and reducing CO_2 emission because of their high specific strength [1]. For their greater applicability, it is required to advance rolling technologies for mass production of Mg alloy sheets. In Mg, the (0002)<11$\bar{2}$0> basal slip takes place preferentially because the critical resolved shear stress (CRSS) for the basal slip is lower than those for the prismatic and pyramidal slips [2]. This gives rise to the poor ductility for a polycrystalline Mg and its alloy. Besides, for rolled Mg alloy sheets, the basal plane is strongly distributed parallel to the RD–TD plane, where the RD and TD are the rolling and transverse directions. In such a case, it is very difficult for the textured sheets to be deformed in the thickness direction [3, 4], resulting in a poor ductility under biaxial tension stress (such as under stretch-forming).

Texture control is an effective way to improve stretch formability of Mg. One of texture control ways is an addition of rare-earth (RE) metal in Mg alloy [5, 6], which modifies and weakens the intensity of basal texture of rolled Mg alloys, attributing to an enhancement of the thickness direction strain (low Lankford value, *r*-value). The other approach for weakening the basal texture intensity is an imposition of the intense shear deformation [7–12]. Another method for improving stretch formability of Mg alloy is a control of grain size. Our previous research [13] has revealed that Mg alloy sheets with coarse grain (around 30 μm) exhibit better stretch formability than those with fine grain (<10 μm). Better stretch formability of Mg alloy sheets with coarse grain size is attributed to an enhanced twin generation.

Recently, Ohtoshi et al. [14] have reported that Mn-free AZ31 (Mg–3.0 wt%Al–1.0 wt%Zn) alloys rolled at high temperature (723 K) and subsequently annealed at 573 K exhibit an enhanced limiting drawing ratio (LDR = 1.7) and a low average *r*-value (1.5 of average *r*-value) at room temperature. However, relationships between grain size, texture, and formability of Mn-free AZ31 alloy rolled at high temperature are still unknown. This paper reports on the relationships between grain size, texture, and stretch formability of Mn-free AZ31 alloy rolled at 723 K.

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Experimental procedure

An as-received Mn-free AZ31 alloy of 50 × 60 × 3.5 mm^3 was heated at 723 K for 1.2×10^3 s in a furnace, and a rolling was conducted at a rolling reduction of 15%, where the roll temperature was held at 353 K. The sheet was rolled to a thickness of 1 mm, and annealed at 618 K for 3.6×10^3 s. A reference Mn-free AZ31 alloy was processed identically to the specimen rolled at 723 K, except that the specimen was heated at 618 K in a furnace before rolling.

A circular blank with a diameter of 60 mm was machined from the specimens. Erichsen tests using a hemispherical punch with a diameter of 20 mm were carried out at room temperature to investigate stretch formability of the specimens, and the Erichsen value (I.E), which was the punch stroke at fracture initiation, was measured. Tensile specimens with 10 mm gage length, 5 mm gage width, and 1 mm gage thickness were machined from the specimens. Tensile tests were carried out at room temperature with an initial strain rate of 1.7×10^{-3} s^{-1}, where the angles between tensile direction and RD were 0, 45, and 90°. Additional tensile tests were conducted to investigate the *r*-value ($r = \varepsilon_w/\varepsilon_t$). The width-direction strain (ε_w) and the thickness-direction strain (ε_t) were measured using the specimens deformed to 10% nominal strain.

A microstructure of rolled Mg alloys was investigated by optical microscopy. Grain size of the specimens was determined by intercept method [15]. Also, twin area ratio of the specimen tensile deformed to 10% nominal strain was estimated by quantitative image analysis using the commercially available software Image-Pro Plus for calculating the area of all present twins and relating this area to the total area of the micrograph. A (0002) plane pole figure of rolled Mg alloy sheets at center through a thickness was investigated by Schulz reflection method. The data were normalized by powder Mg data.

Results and discussion

Microstructures of the rolled specimens after annealing for the TD–ND plane are shown in Fig. 1, where the ND is the normal direction. The average grain size obtained from observations of the RD–TD, RD–ND, and TD–ND planes was 62 and 44 μm for the specimens rolled at 723 and 618 K, respectively. The grain size significantly increased with an increase in the rolling temperature. Note that the grain size of Mn-free AZ31 alloys was much coarser than that of the AZ31B alloys (around 10 μm) [4, 7–10]. This is due to an absence of second phase particles (such as Al_8Mn_5 [16]), which effectively pin a grain growth during hot rolling, in Mn-free AZ31 alloys.

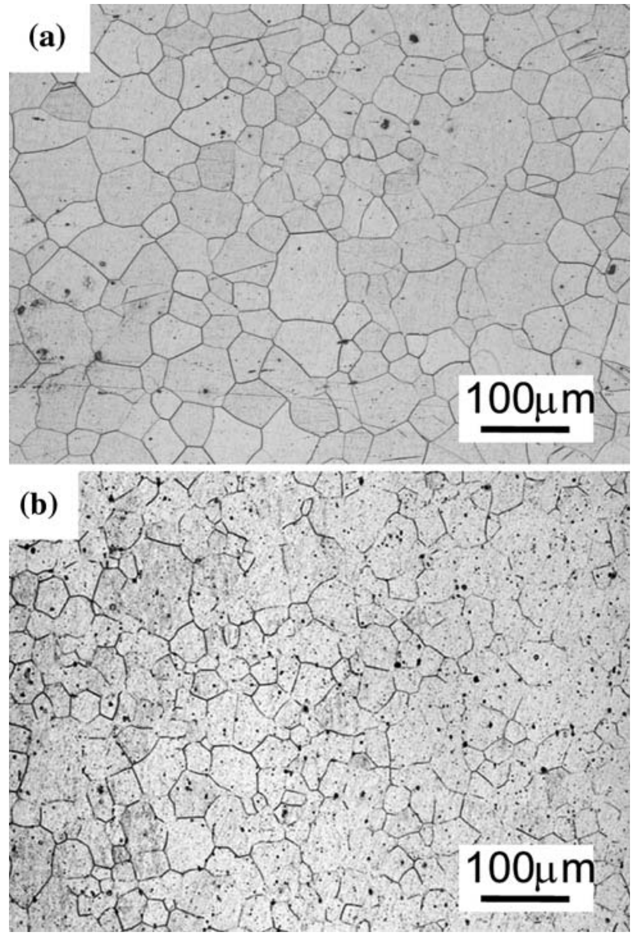

Fig. 1 Optical micrographs of the rolled Mn-free AZ31 alloys after annealing: **a** rolled at 723 K and **b** rolled at 618 K, where the TD–ND plane is observed

The (0002) plane pole figures of the rolled specimens after annealing are summarized in Fig. 2. As a reference, the (0002) plane pole figures of the as-rolled specimens are also shown in Fig. 3. Regardless of rolling temperature, the annealed specimens had almost the same texture with the as-rolled specimens except for the different texture intensity. This texture change during static recrystallization is a typical of conventional Mg alloy sheets [17]. The basal texture of the specimens rolled at 723 K showed lower intensity than the specimen rolled at 618 K, indicating that the high temperature rolling effectively weakened the basal texture. The (0002) plane of the specimen rolled at 618 K was intensively distributed parallel to the RD-TD plane, and there was a spreading of the basal poles toward RD. On the other hand, there was a circular spread of the basal pole from ND in the case of the specimen rolled at 723 K. The tendency to distribute basal pole circularly from the ND is suggested to be due to an activation of non-basal slips during hot rolling [18].

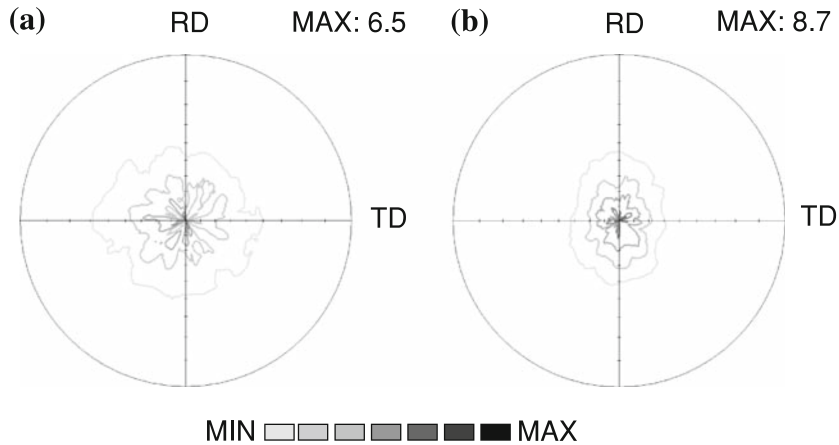

Fig. 2 (0002) pole figures of rolled Mn-freeAZ31 alloys after annealing: **a** rolled at 723 K and **b** rolled at 618 K

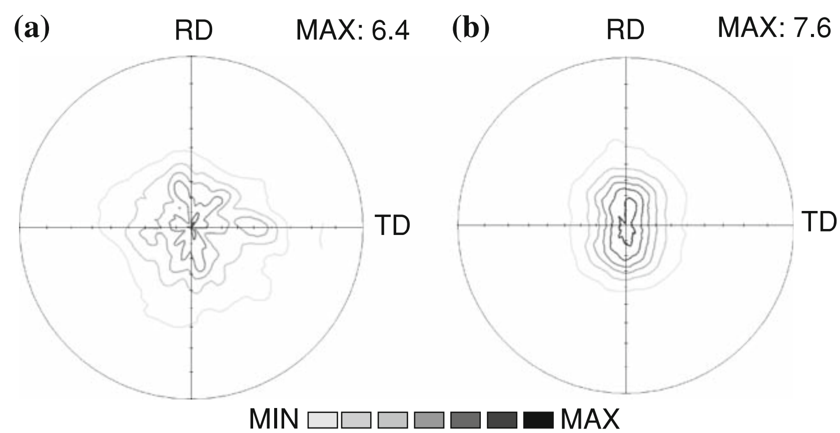

Fig. 3 (0002) pole figures of as-rolled Mn-freeAZ31 alloys: **a** rolled at 723 K and **b** rolled at 618 K

An origin of the weaker basal texture intensity of the specimen rolled at 723 K may be a variation of deformation modes. It is known that a development of basal texture during plane strain compression is caused by an activation of $\{10\bar{1}2\}$ twinning [18]. It is reported that the non-basal slips of Mg show the large temperature dependence of CRSS [19, 20]. On the other hand, the CRSS of $\{10\bar{1}2\}$ twinning is almost independent of temperature (2–3 MPa) [21]. The CRSS of non-basal slips decreases with an increase in temperature, and it reaches the same or lower values compared with that of $\{10\bar{1}2\}$ twinning around 723 K [19–21]. Therefore, a suppression of $\{10\bar{1}2\}$ twinning as well as an activation of non-basal slips likely plays a vital role for the basal texture formation of the specimen rolled at 723 K.

The results of Erichsen tests at room temperature are summarized in Fig. 4. The specimen rolled at 723 K exhibited 1.4 times larger Erichsen value than the specimen rolled at 618 K. It should be noted that the Erichsen value for the specimen rolled at 723 K is superior to that of the shear-rolled AZ31B specimen (4.0 mm) [10]. Thus, it is suggested that the high temperature rolling of Mn-free AZ31 alloy is an effective way for improving the stretch formability at room temperature.

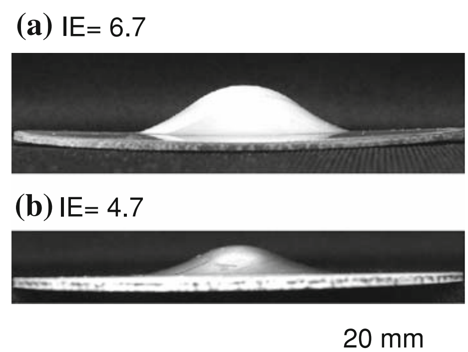

Fig. 4 Specimens after the Erichsen test at room temperature, where **a** Mn-free AZ31 alloy rolled at 723 K and **b** Mn-free AZ31 alloy rolled at 618 K

Tensile properties of the specimens rolled at different rolling temperatures are summarized in Table 1. Note that the average *r*-value of the specimen rolled at 723 K ($r_{ave} = 1.4$) was much lower than that of the specimen rolled at 618 K ($r_{ave} = 3.1$). This result indicates that a thickness-direction strain occurred more for the specimen rolled at 723 K. Assuming that the volume is constant during plastic deformation, the following equation is satisfied:

Table 1 Tensile properties at room temperature for the Mn-free AZ31 alloys rolled at 723 and 618 K

Specimens	Orientation	UTS (MPa)	TYS (MPa)	Elongation (%)	*r*-value	r_{ave}
Rolled at 723 K	0	210	118	20	1.1	1.4
	45	213	111	24	1.5	
	90	218	112	23	1.3	
Rolled at 618 K	0	233	111	16	2.0	3.1
	45	230	114	21	3.5	
	90	223	115	20	3.2	

UTS ultimate tensile stress, *TYS* tensile 0.2% yield stress, r_{ave} average *r*-value

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \quad (1)$$

where ε_l is the longitudinal-direction strain. In the tensile stress, namely, under uniaxial tensile stress, since the longitudinal-direction strain is positive ($\varepsilon_l > 0$), either the width-direction strain or the thickness-direction strain should be negative (ε_w or $\varepsilon_t < 0$). When the (0002) basal planes are strongly distributed parallel to the sheet plane, it is very difficult for the textured sheets to be deformed in the thickness direction, because basal slips only occur in the directions parallel to the sheet plane. Koike et al. [22] investigated the dislocation activity in a fine-grained AZ31B alloy by TEM observation, and they showed that a prismatic slip is activated near the grain boundary by plastic compatibility stress. However, the activated prismatic slip is the <a> slip, not the <c> slip. Hence, the dominant deformation mode under uniaxial tensile stress for the AZ31B alloy is positive longitudinal-direction strain ($\varepsilon_l > 0$) and negative width-direction strain ($\varepsilon_w < 0$). On the other hand, under biaxial tensile stress, since both the longitudinal-direction strain and the width-direction strain are positive (ε_l and $\varepsilon_w > 0$), the thickness-direction strain should be negative ($\varepsilon_t < 0$). This means that straining in the thickness direction should be caused under biaxial tensile stress, that is, lower average *r*-value is essential for better stretch forming of Mg alloy sheet. This is the reason why the (0002) texture is one of critical factors determining Mg stretch formability at room temperature because the straining in the thickness direction is affected by the texture. Therefore, it is suggested that the superior stretch formability of the specimen rolled at 723 K is mainly attributed to the enhancement of thickness-direction strain resulting from the weak basal texture intensity.

The tensile elongation and stretch formability balance in the AZ31B (Mg–3.0 wt%Al–1.0 wt%Zn–0.5 wt%Mn) alloys [4, 10, 13, 23] and the rolled Mn-free AZ31 alloys are shown in Fig. 5. Also, the data of Al alloys are included [23, 24]. The Mn-free AZ31 alloy rolled at 723 K showed good balance with tensile elongation and stretch formability compared with the rolled AZ31B alloys. It is noted that the stretch formability of the specimen rolled at 723 K took the 81% value of that of 5083 Al alloy. Besides, partially noteworthy is that the specimen rolled at 618 K exhibited the same or higher stretch formability compared with the AZ31B alloys despite the minor tensile elongation. This indicates that an application of Mn-free AZ31 alloy makes a contribution to high ductility under biaxial tensile stress (stretch formability) rather than high ductility under uniaxial tensile stress (tensile ductility). Figure 6 shows relationships between grain size and *r*-value in the AZ31B and Mn-free AZ31 alloys. The rolled AZ31B and Mn-free AZ31 alloys with coarse grain size tended to take a low *r*-value, which is one of the essential factors for an enhancement of stretch formability of Mg alloy sheet at room temperature. As shown in Fig. 6, the rolled Mn-free AZ31 alloy in the present study exhibited much coarser grain size than the

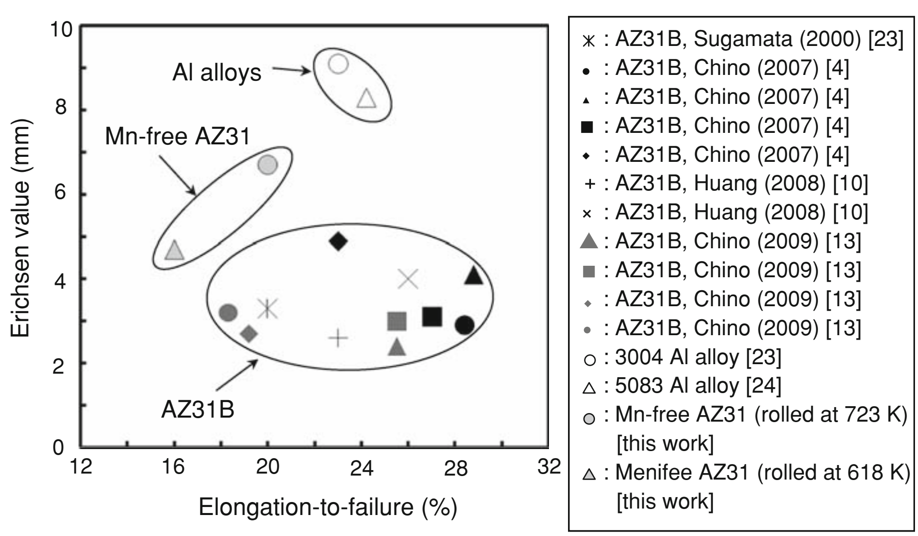

Fig. 5 Relationships between elongation-to-failure and Erichsen value in the AZ31B and Mn-free AZ31 alloys, where the tensile elongation, whose tensile direction was parallel to RD, is adopted. Included are the data for 3004 and 5083 Al alloys [4, 10, 13, 23, 24]

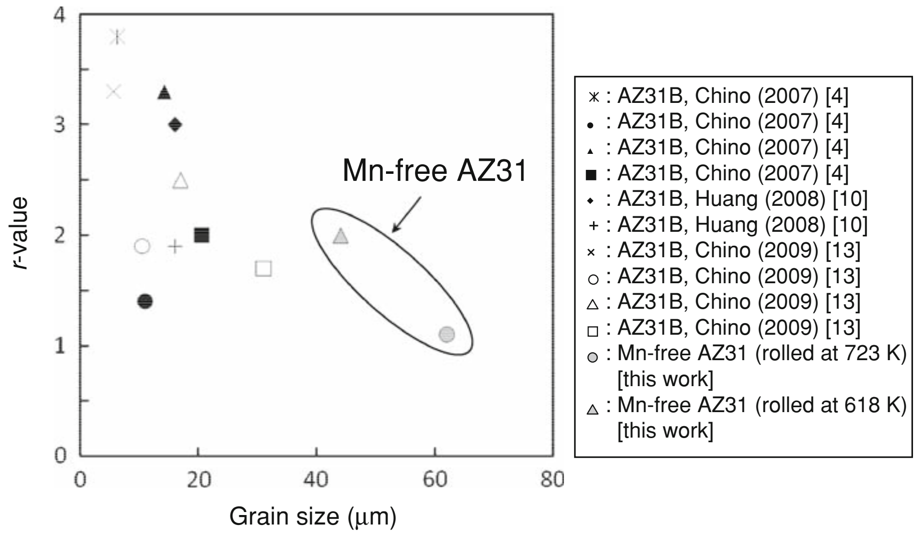

Fig. 6 Relationships between grain size and *r*-value in the AZ31B and Mn-free AZ31 alloys, where the *r*-value, whose tensile direction was parallel to RD, is adopted. [4, 10, 13]

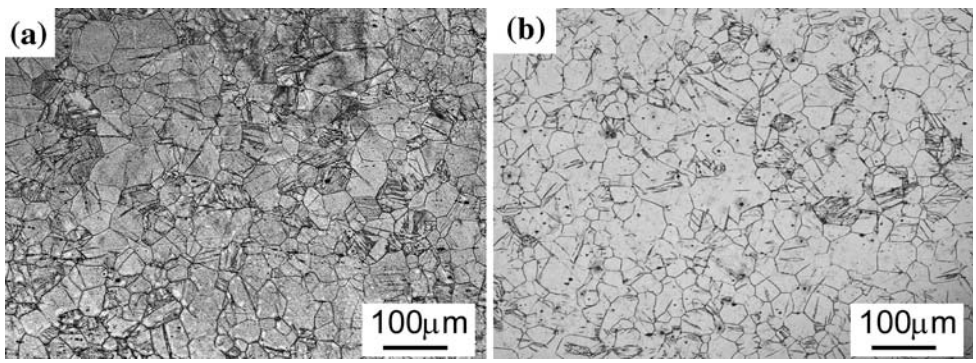

Fig. 7 Optical micrographs of the rolled Mn-free AZ31 alloys tensile deformed to 10% nominal strain, where the angle of tensile direction and RD is 90°, and the TD–ND plane is observed: **a** Mn-free AZ31 alloy rolled at 723 K and **b** Mn-free AZ31 alloy rolled at 618 K

AZ31B alloys in the previous study. Thus, the enhanced stretch formability of the Mn-free AZ31 alloy is suggested to be closely related to the coarse grain size.

One possible reason for the superior stretch formability of Mn-free AZ31 alloys is a variation of twinning mode due to a difference in grain size. Figure 7 shows microstructures of the specimens rolled at 723 and 618 K deformed to 10% nominal strain by tensile tests, where the TD–ND plane is observed. The twin area ratio measured by the image analysis was 14.1% for the specimen rolled at 723 K and 5.5% for the specimen rolled at 618 K. More deformation twins were observed in the specimen rolled at 723 K. It is reported that $\{10\bar{1}2\}$ twins become easily generated during tensile loading, when Mg alloys exhibit a weak basal texture intensity due to high Schmid factor for the twinning [25, 26]. This may be responsible for the larger twin area ratio of the specimen rolled at 723 K. It should be noted that the twin area ratio of the specimen rolled at 618 K (5.5%) is still much larger than that of tensile deformed AZ31B alloy (around 1.0%), whose grain size is around 10 μm [26]. It is known that energy of twin interfaces is significantly large in Mg and twin nucleation decreases with decreasing grain size [22], that is, twin formation is enhanced by grain coarsening. Thus, it is suggested that coarse grain size of Mn-free AZ31 alloys significantly promotes twin generation during tensile deformation. Our previous study [13] has revealed that stretch formability of rolled AZ31B alloy is improved with an increase in grain size. The enhanced stretch formability of the AZ31B alloy with coarse grain size is related to a generation of twins, because a lattice rotation by twinning (such as $\{10\bar{1}1\}$ twinning) results in an increase in Schmid factor for the basal slip in the twins. Therefore, it is suggested that the enhanced basal slip due to lattice rotation by twinning likely plays an important role inducing high thickness-direction strain of Mn-free AZ31 alloys.

Conclusion

Stretch formability of Mn-free AZ31 Mg alloy rolled at high temperature (723 K) was investigated at room temperature, and origins of the enhanced stretch formability were discussed.

The specimen rolled at 723 K showed superior stretch formability to that of the specimen rolled at 618 K. The (0002) plane texture of the specimen rolled at 723 K exhibited lower texture intensity compared with that of the specimen rolled at 618 K. It is suggested that the modification of basal texture by the high temperature rolling contributed to an activation of basal slip, resulting in an enhancement of the stretch formability. Besides, it is suggested that coarse grain size of a Mn-free AZ31 alloy seems to enhance a stretch formability, because twins become easily generated during tensile loading.

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