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Analysis of formability of Ca-added magnesium alloy sheets at low temperatures

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ABSTRACT

The formability of sheets of the Ca-added magnesium alloy AZX311 was analyzed. The parameters affecting the sheet formability, such as the strain-hardening rate and the strain-rate sensitivity, did not seem to be higher in the alloy AZX311 at temperatures of room temperature (RT) and 200 °C. In addition, the critical stress for fracture at RT was lower in AZX311 than in AZ31. However, AZX311 exhibited higher stretchability and formability at low temperatures than AZ31. Electron back-scattered diffraction microscopy revealed that AZX311 had a weaker basal texture as well as broadened basal poles along the transverse direction. Polycrystal plasticity simulations confirmed that this weaker basal texture increases the activity of basal slip over thickness strain, resulting in the higher formability of AZX311.

1. Introduction

Magnesium alloys have the lowest density of all structural metals and exhibit high specific strengths. Therefore, many industries – in particular the automotive industry – have made significant efforts to extend the applicability of magnesium alloy sheets in areas where weight reduction is necessary. However, the use of such sheets is restricted because of several reasons. One of them is their poor formability at low temperatures. Hot-rolled magnesium sheets exhibit strong {0001} texture along the thickness direction, which make it difficult to accommodate deformation in that direction [1,2]. There have been many attempts to tilt or weaken the texture to improve formability [3,4]. The texture can be control by specialized rolling processes such as shear rolling, high-temperature rolling, and high-temperature annealing and subsequent warm rolling [5–7], by adding a rare earth element, such as Ce, Y, Gd, and La [8–10], and by generating tensile twin [11–13].

In parallel, modeling and simulation methods were developed to understand the mechanism of deformation and texture evolution in magnesium alloys. Hama et al. predicted work hardening behavior in a magnesium alloy sheet under biaxial tension using crystal plasticity finite element method (CP-FEM) [14]. Li et al. applied the intermediate viscoplastic phi-model to predict mechanical behavior of magnesium alloy during rolling and uniaxial loading [15]. Muhammad et al. proposed an anisotropic continuum-based plasticity model to describe asymmetric/anisotropic hardening behavior of magnesium alloy during cyclic loading [16].

It has been reported that the addition of Ca can effectively weaken or tilt the basal texture in pure Mg as well as in Mg–Zn and Mg–Al alloys during rolling and annealing, so that the stretchability of these alloys at room temperature (RT) is improved [17–19]. However, the effects of the addition of Ca on the formability of sheets of the magnesium alloy AZ31, which is the most commonly used magnesium alloy, have not yet been understood clearly.

In this study, the formability of sheets of the Ca-added magnesium alloy, AZX311 was analyzed at low temperature using tensile and limit dome height (LDH) tests as well as through die forming. The obtained results were compared with those for the magnesium alloy AZ31. To elucidate the mechanism responsible for the improvement in formability, several parameters related to the resistance to plastic instability were measured. Further, the effect of initial texture on the formability was analyzed based on the slip and twin activities.

2. Experimental procedures

As noted above, the materials used in this study were commercial twin roll cast sheets of the alloys AZ31 (Mg–3 Al–1 Zn; wt.%) and AZX311 (Mg–3 Al–1 Zn–1 Ca; wt.%); the sheets had a thickness of 1.2 mm and were produced by POSCO.

The initial microstructures of the AZ31 and AZX311 specimens were measured in the plane normal to the transverse direction (TD); a field-emission scanning electron microscopy (FE-SEM) equipped with an EBSD instrument was employed for the purpose. The EBSD images

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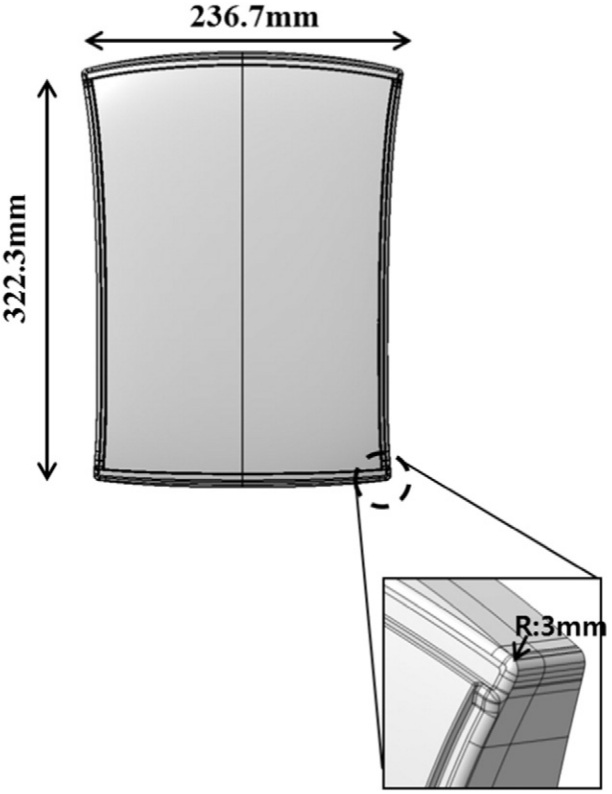


Fig. 1. Schematic diagram of the subsized (1/4) roof die.

Table 1
The CRSS and hardening responses of the four deformation mechanisms for the VPSC simulation.

Mode	AZ31				AZX311			
	τ_0	τ_1	θ_0	θ_1	τ_0	τ_1	θ_0	θ_1
Basal	23.5	5	150	0.1	28	5	130	0.1
Prismatic	100	5	200	0.1	110	10	180	0.5
<c + a>	200	30	150	0	125	85	320	
Twin	34.2	0	0	0	37.5	0		

were acquired for a step size of 0.5 μm. To identify the intermetallic compounds formed, energy-dispersive X-ray spectroscopy (EDS) was used.

The specimens for the tensile tests were machined and had a gauge length of 25 mm. The tensile tests were performed at a strain rate of 10^{-3} s^{-1} at RT and 200 °C along the rolling direction (RD), at an angle of 45°, and along the TD. The strain-rate sensitivity was measured for strain rates ranging from 10^{-3} to 0.1 s^{-1} at RT and 200 °C. The stretchability of the alloys was measured through LDH tests. The alloy sheets were machined into disk-shaped specimens with a diameter of 50 mm for the LDH tests, which were performed using a hemispherical punch with a diameter of 20 mm at a punch speed of 0.1 mm/s at RT. All the mechanical tests were repeated five times for each condition, in order to obtain reliable data. To compare the formability of the two alloys in the complex deformation mode, forming test was conducted at various temperatures using a sub-sized roof die, which was 1/4 the size of an actual roof die. A schematic diagram of the die is shown in Fig. 1. The specimens were preheated to the nominal forming temperature. Heating cartridges were placed inside the die, and the die was heated to the nominal forming temperature. An 800-ton servo press was used; it had a cyclic speed of 5 mm/min. To reduce the friction between the die and the specimen being formed, a Teflon sheet with a thickness of 0.1 mm was used.

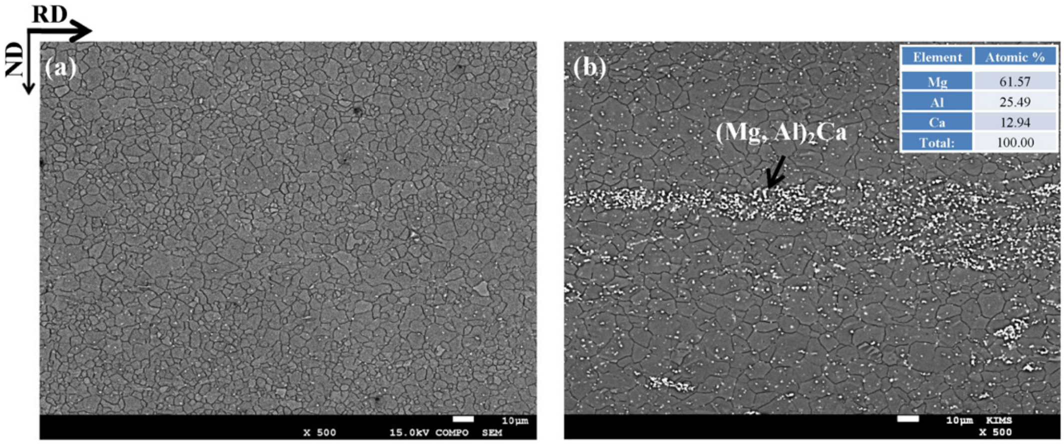
2.1. VPSC modeling

The viscoplastic self-consistent (VPSC) model [20] was used to analyze texture effect on deformation behaviors of both specimens. A detailed description of the VPSC model can be found in elsewhere [20, 21]. In summary, the viscoplastic formulation of the model describes inhomogeneous ellipsoidal inclusion embedded in a homogeneous medium with averaged properties of other grains.

In this study, the measured orientations of both specimens were used as the input texture. Because it has been reported that non-basal <a>-type slips in magnesium alloys can be modeled accurately using only a prismatic slip [22], three slip systems (namely, the basal, prismatic, and <c + a> pyramidal slip systems) were considered for the simulation along with the tensile twin. The extended Voce law was incorporated in the VPSC method to model hardening response of the individual slip and twinning systems by increasing the critical resolved shear stresses, τ^s_{ref} for the *s*th systems, as a function of the total accumulated shear strain in the grain, Γ.

$$\tau^s_{ref} = \tau^s_0 + \left(\tau^s_1 + \theta^s_1 \Gamma\right)\left[1 - \exp\left(-\frac{\theta^s_0 \Gamma}{\tau^s_1}\right)\right] \qquad (1)$$

$\theta^s_0, \theta^s_1, \tau^s_0$, and $(\tau^s_0 + \tau^s_1)$ are the initial and final slopes of the hardening curve, initial critical resolved shear stress (CRSS), and the back-extrapolated CRSS, respectively. Self and latent hardening for



Element	Atomic %
Mg	61.57
Al	25.49
Ca	12.94
Total:	100.00

Fig. 2. Backscattered electron (BSE) images of the (a) AZ31 and (b) AZX311 specimens.