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Enhancing mechanical properties of rolled Mg-Al-Ca-Mn alloy sheet by Zn addition

T. Nakata[a,*], C. Xu[a], K. Suzawa[b], K. Yoshida[b], N. Kawabe[b], S. Kamado[a]

[a] Nagaoka University of Technology, 1603-1, Kamitomioka, Nagaoka 940-2188, Japan
[b] Sumitomo Electric Industries, LTD. 1-1-1, Koyakita, Itami-shi, Hyogo 664-0016, Japan

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ABSTRACT

A strong and ductile Mg-8Al-1Zn-1Ca-0.3Mn (wt%) alloy sheet has been successfully developed via commercial rolling process. The ultimate tensile strength, 0.2% proof stress, and elongation to failure along the rolling direction of the sheet are 371 MPa, 275 MPa, and 17.1%, respectively. The high strength and ductility are attributed to the fine recrystallized grains and densely dispersed fine $Mg_{17}Al_{12}$ precipitates. Further, due to its isotropic basal texture, the Mg-8Al-1Zn-1Ca-0.3Mn alloy sheet shows little in-plane anisotropy. The ultimate tensile strength, 0.2% proof stress, and elongation to failure along the 45° and transverse direction of the sheet are almost the same as those in the rolling direction. The good tensile properties can be realized by using only inexpensive ingredients and commercial rolling process; therefore, the Mg-8Al-1Zn-1Ca-0.3Mn alloy sheet will be a candidate as structural materials for transportation vehicles.

1. Introduction

Development of strong and ductile magnesium (Mg) alloy sheet is strongly desired to reduce the weight of transportation vehicles such as cars and high-speed trains. Accumulative roll bonding (ARB) has been proposed to dramatically increase strengths of Mg alloy sheets. A commercial Mg-9Al-1Zn (wt%, AZ91) alloy sheet produced by the ARB method exhibits ultimate tensile strength (UTS) of 405 MPa and 0.2% proof stress (PS) of 350 MPa [1]. Large strain rolling has been also applied to achieve high strength and ductility. Commercial Mg-Al and Mg-Zn based alloy sheets processed via large strain hot rolling show UTS over 370 MPa, PS over 270 MPa, and elongation to failure (EF) of around 10–20% [1–3]. Above rolling process successfully enhances both strengths and ductility of rolled Mg alloy sheets; however, they are difficult to operate in real manufacturing process. Alloy development is also one of the trends to obtain Mg alloy sheets with high mechanical property. As a strong and ductile rolled Mg sheet, Ag microalloyed Mg-6Zn-0.5Zr-0.2Ca-0.4Ag (ZXQK6000) alloy sheet has been developed. After an aging, the ZKQX6000 alloy sheet exhibits high UTS, PS, and moderate EF of 336 MPa, 300 MPa, and 12.4%, respectively [4]. Mg-Gd based alloy sheet also shows high strengths and ductility. UTS, PS, and EF of 393 MPa, 306 MPa, and 14.6% have been realized in a rolled Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr alloy sheet [5]. Although the addition of Ag or RE element can dramatically improve the mechanical properties, these elements are expensive, suggesting that alloys containing such elements are not suitable for practical uses. Ca is a cost-effective alloying element that can increase strengths and ductility of magnesium by solid-solution strengthening, dispersion of precipitates, and decreasing of anisotropy in critical resolved shear stress [6–8]. In addition, Ca-containing alloys are regarded as attractive materials for transportation vehicles due to their high ignition resistance [9]; therefore, Ca is added to Mg-Al based alloys, and the microstructures and mechanical properties of the extruded [10–14] and rolled [15,16] Mg alloys are investigated energetically. However, the investigation is mainly focused on Mg alloys with Al content less than 6%. Since the high content of Al is prerequisite to improve corrosion resistance [17], high mechanical properties should be realized in Mg alloys with high content of Al and moderate content of Ca.

Zn is one of the promising constituent elements to improve the mechanical properties of wrought Mg-Al based alloys [18]. However, in the Mg-Al-Zn based alloys, the addition of Zn over 1% significantly deteriorate the weldability [19], which means maximum Zn content should be limited to 1% for structural components. Considering these backgrounds, in this work, we have investigated the effect of Zn content up to 1% on mechanical properties and microstructures of a Mg-8Al-1Ca-0.3Mn (AX81) alloy sheet, and tried to improve the mechanical properties of a rolled AX81 alloy sheet.

* Corresponding author.
E-mail address: nakata@mech.nagaokaut.ac.jp (T. Nakata).

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Table 1
Nomenclatures and chemical compositions of rapidly solidified alloy ingots used in this work [wt% (at%)].

Alloy	Al	Zn	Ca	Mn	Mg
AX81	7.5 (6.8)	–	1.07 (0.66)	0.17 (0.08)	Bal.
AZX8031	8.7 (8.0)	0.28 (0.11)	0.97 (0.60)	0.29 (0.13)	Bal.
AZX811	8.1 (7.4)	1.0 (0.38)	0.96 (0.59)	0.31 (0.14)	Bal.

2. Experimental procedure

Rapidly solidified sheets with nominal compositions of Mg-8Al-1Ca-0.3Mn, Mg-8Al-0.3Zn-1Ca-0.3Mn, and Mg-8Al-1Zn-1Ca-0.3Mn (wt%, AX81, AZX8031, and AZX811) were prepared by a twin-roll-casting technique. A small amount of Mn was added to improve the corrosion resistance [20], and the thickness of the rapidly solidified sheets was 4 mm. Table 1 summarizes the nomenclatures and chemical compositions of the rapidly solidified sheets in both wt% and at%. Homogenization treatment was carried out at 415 °C for 2 h plus 450 °C for 2 h with an increasing rate of 1 °C/min, followed by water quenching. After the homogenization, samples were subjected to a hot-rolling. The surface temperatures and the peripheral speeds of the rollers were 300 °C and 40 m/min, respectively. The rolling procedure was consisted of six passes with a constant rolling reduction of thickness, each referring to a strain:

$$\varphi = (h_n - h_{n+1})/h_n = 0.2, \quad (1)$$

where n is the number of the rolling pass and hn is the sample thickness after the rolling pass n. Before the rolling, the homogenized samples were pre-heated at 300 °C for 10 min, and the rolling was carried out to obtain the sheets with 1 mm in thickness without re-heating the samples. After the rolling, the sheets were cooled in an air. Tensile properties of the as-rolled sheets were evaluated at room temperature with an initial strain rate of 10^{-3} s^{-1} using an Autograph AG-I 50 kN (Shimazu). For the tensile tests, specimens were taken from the sheets in three orientations: rolling direction (RD), 45°, and transverse direction (TD). The tensile test specimens had 50 mm in gauge length and 12.5 mm in width, and the test was repeated five times for each conditions. To evaluate the normal anisotropy, the tensile test in each orientation was interrupted at a strain of 8%, and Lankford-value (r-value) was determined by a following equation;

$$r = \varphi_w / \varphi_t, \quad (2)$$

where φ_w and φ_t are the true plastic strains along the sample width and thickness, respectively. The r-value was calculated from three interrupted specimens. To characterize the microstructures of the as-rolled sheets, a scanning electron microscope (SEM, JEOL JSM-7000F) with an electron backscattered diffraction system (EBSD, TSL), and a transmission electron microscope (TEM, JEOL JEM-2100F) with an EDS detector and a high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) detector were used. Thin foils for the TEM observations were prepared by punching discs of 3 mm diameter, mechanical polishing, and ion-milling using a Gatan Precision Ion Polishing System (PIPS).

3. Results

Fig. 1 shows tensile stress-strain curves of the as-rolled AX81, AZX8031, and AZX811 alloy sheets stretched along the **(a)** RD, **(b)** 45°, and **(c)** TD. Table 2 summarizes their ultimate tensile strength (UTS), 0.2% proof stress (PS), and elongation to failure (EF). The UTS, PS, and EF of the AX81 alloy sheet stretched along the RD are 343 MPa, 252 MPa, and 14.3%, respectively. The AX81 alloy sheets stretched along the 45° and TD show similar UTS, PS, and EF as the RD-stretched sample. The 0.3% Zn addition enhances strengths. The RD-stretched AZX8031 alloy sheet exhibits higher UTS and PS of 376 MPa and 276 MPa than those of the AX81 alloy sheet. The AZX8031 alloy sheet also shows small in-plane anisotropy of strengths as the AX81 alloy sheet. The AZX8031 alloy sheet shows UTS and PS of 378 MPa and 273 MPa along the 45° and 374 MPa and 276 MPa along the TD. However, the 0.3% Zn addition deteriorates the ductility. Compared to the AX81 alloy sheet, the AZX8031 alloy sheet shows low EF of 13.8% and 13.0% in the RD and 45°, and its EF along the TD is only 11.6%. Increasing Zn content up to 1% does not lead further improvement in strengths. The AZX811 alloy sheet shows UTS and PS of 371 MPa and 275 MPa in the RD, 372 MPa and 274 MPa in the 45°, and 372 MPa and 279 MPa in the TD. Although the strengths are not enhanced by the high content of Zn, it is worthy to note that, the 1% of Zn addition increases the ductility. The EF in the RD-stretched AZX811 alloy sheet is 17.1%. Further, the AZX811 alloy sheet also shows high EF of 17.8% in the 45° and 16.9% in the TD. Table 3 summarizes the r-values determined from the 8% stretched samples. The r_{RD}, r_{45}, and r_{TD} in the Table 3 represent the r-values obtained from the samples stretched along RD, 45°, and TD, respectively, and the r_{avg} represents the average r-value calculated from the following Eq. (3);

$$r_{avg} = (r_{RD} + 2r_{45} + r_{TD})/4, \quad (3)$$

The r-values of all samples are in the range of 1.4–1.6, and their average r-values are about 1.6, which means that the normal anisotropy is not strong as a commercial AZ31 alloy sheet in all samples [21].

Fig. 2 shows inverse pole figure maps of the as-rolled **(a)** AX81, **(b)** AZX8031, and **(c)** AZX811 alloy sheets. These images were taken from the TD. The AX81 alloy sheet mainly consists of equi-axed grains with average recrystallized grain size of 5.3 μm. The area fraction of un-

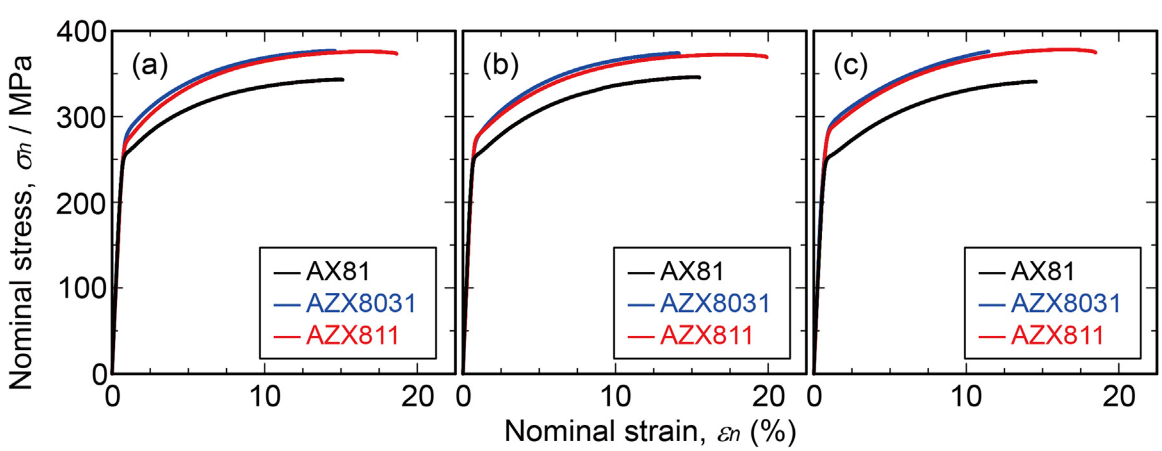

Fig. 1. Tensile stress-strain curves of as-rolled AX81, AZX8031, and AZX811 alloy sheets stretched along (a) RD, (b) 45° and (b) TD.