Tensile property and cold formability of an $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet with long-period ordered phase

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Abstract

The tensile property and cold formability of a $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet containing Mg-, long-period ordered (LPO)-, and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ - phases were investigated. The $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet exhibited high yield stress of 320 MPa and elongations of 11 % at room temperature and could be prepared by hot-rolling. After, annealing at 773 K for 0.6 ks, although the yield stress decreased to 200 MPa, elongation increased to 20 %. Texture randomization due to re-crystallization of the Mg phase occurred in the annealed $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet was confirmed by EBSD analysis. The formability of a $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet and an AZ31-O sheet was evaluated via a 90° V-bending test at room temperature. The annealed $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet could be bent without cracking with a minimum bending radius per thickness of $R/t = 3.3$, which is less than that of as-rolled $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet and the AZ31-O sheet. This improvement in the cold formability of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet considered due to an increase in randomness of the Mg phase that results from re-crystallization of the Mg phase.

1. Introduction

An advantage of working with magnesium is that it has the lowest density (1.74 g/cm^3 ; about two-thirds that of aluminum and one-fourth that of iron) among all structural metallic materials. In 2001, a rapidly solidified powder/metallurgy (RS P/M) $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ (at.%) alloy with a yield stress (σ_y) above 600 MPa and a 5 % elongation (δ) at room temperature was reported [1,2]. The excellent mechanical properties of this Mg-Zn-Y alloy are attributed not only to the grain refinement of the Mg phase, but also to a long-period ordered (LPO) phase with a fine lamellar structure that is included in each grain. Hereafter, various 10H-, 14H-, 18R-, and 24R-type LPO structures were systematically observed in Mg-M-Y alloys (M = Cu, Ni, or Zn) and in their thermally treated states [3-9]. Recently, high strength Mg alloys, such as Mg-Zn-Y extruded bar or Mg-Ni-Y alloy sheet have been developed using the LPO phase as a strength phase. [9.10] For instance, $\text{Mg}_{90.5}\text{Ni}_{3.25}\text{Y}_{6.25}$ (at.%) alloy sheet with the LPO (18R-type) phase exhibited a high σ_y of 470 MPa and a reasonable δ of 8 % at room temperature. Furthermore, at 473 K, this material exhibited a σ_y greater than 300 MPa [9]. Mg alloy sheets are currently being tested for various applications such as for thin components with large surface areas; hence, high strength Mg alloy sheets with good cold formability are required to extend the use of Mg alloys to such fields. However, few investigations exist on the tensile property and cold formability of Mg alloy sheets with the LPO phase prepared by the rolling process. Recently, Kohzu *et al.* reported that randomizing the texture of the Mg phase in AZ31 sheets considerably improve the cold formability of this material [11]. This study investigated the tensile property and microstructure of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheets. Furthermore, cold formability of the alloy sheets was evaluated by 90° V-bending test at room temperature.

2. Experimental Procedure

An alloy ingot of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ (at.%) was prepared from pure Mg, Zn, and Y by an electric-furnace melting in an iron-crucible under a CO_2 atmosphere, and followed by casting into a steel die. The cast ingot was re-melted and then cast into a water-cooled Cu mold ($5 \times 15 \times 100 \text{ mm}^3$) to avoid segregation of the solute elements by rapid solidification. The cast alloy was rolled at 693 K to 90 % thickness reduction and the rolled sheet was annealed at 773 K for 0.6 ks in air. A tensile test was performed with a strain rate of $6.5 \times 10^{-4} \text{ s}^{-1}$ at room temperature. The microstructures were examined with a scanning electron microscope (SEM; JSM-5300LV) and a transmission electron microscope (TEM; JEM-4000FX) operating at 400 kV. The basal plane pole figure was measured up to 60° using the Schultz reflection method with an x-ray diffractometer (XRD; JDX3530). The grain orientation was studied using electron backscattering diffraction (EBSD) equipped with a SEM (JEM-7001F). The minimum bending radii per thickness of R/t for various radii R (where R is the tip radius of punches and t is the sheet thickness) is shown in Table 1. The V-bending limit was checked with the SEM and V-bending tests were performed at cross-head speeds of 0.83 mm/s.

3. Results and discussions

Figure.1 (a) shows an SEM backscatter electron image (BEI) of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. The black and gray contrasts correspond to the Mg and LPO phases, respectively. The arrows in Fig. 1 (a) indicate brighter contrast phases 1 to 5 μm in size. The XRD results indicate that the cast alloy consists of Mg, LPO, and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases. Therefore, the areas of brighter contrasts are attributed to the $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phase. Figure 1

(b) shows an electron diffraction pattern from the LPO phase in the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. The arrows indicate the extra reflection spots at the positions of $n/6$ (0002) hcp (where n is an integer). Also, it can be recognized that the $(30\bar{3}0)$ is perpendicular to the c -axis, so the diffraction pattern indicates an 18R-type LPO structure. Figure 1 (c) shows a BEI of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks. The Mg-, LPO-, and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases were confirmed by XRD pattern taken from the annealed sheet. From the figure, elongated LPO phases toward the rolling direction (RD) were observed. Furthermore, it can be found that $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases below 1 μm in size are uniformly dispersed in the Mg matrix (see arrows). After annealing, the morphologies of the LPO and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases remain essentially the same as those before annealing. Figure 1 (d) shows a (0002) pole figure of the annealed sheet. Because the basal-plane diffraction angle of the LPO phase is nearly identical to that of the Mg phase, the (0002) pole figure shows basal planes in both the Mg and LPO phases. As shown in Fig. 1 (d), the peak tilts about 10° from the nominal direction (ND) toward the RD and spreads toward the transverse direction (TD). By rolling, the basal planes of both the LPO and Mg phases become oriented close to the sheet's plane [8]. Because an elongated LPO phase is observed in the annealed sheet, it can be considered that the basal-plane texture shown in Fig. 1 (d) is significantly influenced by the basal-plane texture of the LPO phase. However, the maximum texture intensity in the pole figure of the annealed sheet is 3.4, which is lower than that of the as-rolled sheet (11.1). These results indicated that the microstructure is changed in the Mg phase for the annealed sheet.

Figure 2 shows an inverse pole figure (IPF) image acquired by EBSD analysis from the Mg phase taken from a plane of the annealed sheet. Figure 2 also shows the

calculated (0001) , $(10\bar{1}0)$ and $(2\bar{1}\bar{1}0)$ pole figures. Black contrasts in the IPF image correspond to LPO or $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases which are un-identified areas. Mg grains ranging from 5 to 30 μm in size are apparent in the IPF image. The peak in the (0001) pole figure deviates from the ND to the TD and is spread between the two directions. Furthermore, the peaks in the $(10\bar{1}0)$ and $(2\bar{1}\bar{1}0)$ pole figures are also spread between the RD to the ND. These results indicate that, by simple annealing, the strong basal-plane texture of the Mg phase is considerably reduced by randomization caused by the re-crystallization.

A tensile test was performed along the RD for the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet and its annealed sheet at room temperature. The as-rolled sheet exhibits a σ_y of 320 MPa, and δ of 11 %, respectively. Although the σ_y decreased to 200 MPa, the δ increased to 20 %. The microstructure suggests that the strength factor of the alloy sheet is due to the formation of basal-plane texture in the LPO phase (basal plane is perpendicular to the ND) and to uniform dispersion of a fine $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phase.

To evaluate the cold formability, a 90° V-bending test was performed at room temperature with the as-rolled sheet and the annealed sheet. For comparison, the V-bending test was also performed with an AZ31-O sheet. The $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy was rolled at 693 K to a thickness reduction of 84%, so that it was the same thickness as the AZ31-O sheet. A $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet was annealed at 773 K for 0.6 ks to re-crystallize the Mg phase. Table 2 shows the V-bending limit of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet, this same sheet after annealing, and the AZ31-O sheet. For the annealed sheet, $R/t = 3.3$, which is lower than that for the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet ($R/t = 5.0$) or for the

AZ31-O sheet ($R/t = 3.8$). Figure 3 shows an SEM image acquired after the V-bending test for $R/t = 3.3$ for (a) the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks and (b) the AZ31-O sheet. After the V-bending test, a crack appears in the AZ31-O sheet, as indicated by the arrow in Fig. 3 (b). This result clearly indicates that the cold formability of the annealed sheet is better than that of the AZ31-O sheet.

From these results, it can be concluded that randomizing the Mg phase is effective not only in increasing the elongation but also in improving the cold formability at room temperature. Therefore, the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet strengthened by LPO and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases with good cold formability can be prepared by simple annealing of the as-rolled sheet.

4. Conclusions

The $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet exhibited high yield stress of 320 MPa and elongation of 11%. By annealing at 773 K for 0.6 ks, the basal-plane texture of the Mg phase in the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet was considerably reduced by randomization due to re-crystallization of the Mg phase. The minimum bending radius per thickness of the annealed sheet is 3.3, which is less than that of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet or the AZ31-O sheet. Thus, a high-strength $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet could be prepared by hot-rolling, and simple annealing of the as-rolled sheet leads to good cold formability.

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Figures and captions

Figure 1. (a) SEM (BEI) image of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. (b) Electron diffraction pattern of LPO phase formed in $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. (c) SEM (BEI) image of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks. (d) Annealed $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet (0002) pole figure.

Figure 2. IPF map of Mg phase in $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks.

Calculated pole figures for (0001) , $(10\bar{1}0)$ and $(2\bar{1}10)$ are also shown.

Figure 3. SEM images acquired after V-bending test with $R/t = 3.3$ for (a) $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks and for (b) AZ31-O sheet.

Table 1. Ratio R/t in V-bending tests, where R is the tip radius of punches and $t = 0.8$ (mm) is the sheet thickness. Schematic of the V-bending test with dimensions is also illustrated.

Table.2 V-bending limit of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet, $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks, and AZ31-O sheet. After the V-bending test, cracks in bent sheets were observed using an SEM. The (non)occurrence of a crack in a bent sheet is denoted by $(\circ) \times$.

Figure 1. (a) SEM (BEI) image of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. (b) Electron diffraction pattern of LPO phase formed in $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ cast alloy. (c) SEM (BEI) image of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks. (d) Annealed $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet (0002) pole figure.

Figure 2. IPF map of Mg phase in $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks. Calculated pole figures for (0001), $(10\bar{1}0)$ and $(2\bar{1}\bar{1}0)$ pole figures calculated this image are also shown.

Figure 3. SEM images acquired after V-bending test with $R/t = 3.3$ for (a) Mg₉₆Zn₂Y₂ alloy sheet annealed at 773 K for 0.6 ks and for (b) AZ31-O sheet.

Table 1. Ratio R/t in V-bending tests, where R is the tip radius of punches and $t = 0.8$ (mm) is the sheet thickness. Schematic of the V-bending test with dimensions is also illustrated.

R / mm	4.0	3.0	2.6	1.7
R/t	5.0	3.8	3.3	2.2

Table.2 V-bending limit of $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet, $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks, and AZ31-O sheet. After the V-bending test, cracks in bent sheets were observed using an SEM. The (non)occurrence of a crack in a bent sheet is denoted by (○) !"#

R/t	5.0	3.8	3.3	2.2
$\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet	○	×	×	×
AZ31-O sheet	○	○	×	×
$\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy sheet annealed at 773 K for 0.6 ks	○	○	○	×