Effect of Cross-Roll Angle on Microstructures and Mechanical Properties during Cross-Roll Rolling in AZ31 Alloys

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The objective of this study was to investigate the cross-roll rolling process effects on microstructures and mechanical properties of AZ31 Mg sheet about rolling angle, in which the roll axes were tilted 0°, 2.5°, 5° and 7.5° away from the transverse direction. Three-dimensional FEM simulation proved that increasing the cross-roll angle, the through-thickness variation of effective strains decreases extremely. The cross-roll rolled and subsequently annealed samples have the uniform and fine grain size at whole thickness layers with increasing the cross-roll angle from 0° to 7.5°. The result of tensile test discloses that while the increase in cross-roll angle can scarcely affect on the strength of samples, it can improve the formability of samples remarkably. [doi:10.2320/matertrans.M2011260]

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1. Introduction

Magnesium alloys having sound mechanical properties such as lower density (1.74 g/cm³) than aluminum alloys (2.7 g/cm³) and steel (7.8 g/cm³) and high specific strength have been used as one of the promising light weight structural materials.1) Recently, the use of magnesium alloys has been increasing steadily to achieve weight reduction of transportation as well as electronic industries. However, magnesium alloys having very low ductility near room temperature are restricted using as applications of wrought products.2) It is well known that magnesium has less than five independent slip systems required for general plastic deformation of poly crystalline materials to be uniform deformation without fracture. The hexagonal close packed (HCP) structures of Mg alloys only provide the two independent slip systems; basal slip and prismatic slip.3–5) Therefore, warm forming is needed for processing of Mg alloys at high temperature.6) Many researchers have attempted to improve formability of Mg alloys,7,8) such as by adding some alloying elements, by controlling microstructures.11,12) Among the above, the last one is to control microstructures such as grain refinement and texture modification for magnesium alloys by DSR, ARB, ECAP and ECAR. Recently, Chino et al. reported that the cross-roll rolling is effective for the imposition of severe shear strain on rolled materials compared to conventional roll rolling, leading to an improvement of microstructure and formability of magnesium alloy sheets.13–17) However, the studies of cross-roll rolling have been limited to just few researchers and especially the effect of cross-roll angle between upper roll and lower roll during cross-roll rolling has not yet been found. In the present study, cross-roll rolling with various tilted roll axes was carried out in AZ31 alloy sheets. The effect of cross-roll angle on grain refinement and mechanical properties was investigated. Also, the evolution of strain states during cross-roll rolling according to tilted roll axes was investigated by three-dimensional finite element method (FEM).

2. Experimental Procedures

The material used in this study was commercial AZ31 alloy. The initial specimen size was about 70 mm × 70 mm × 4 mm (width, length and thickness). Rolling was conducted using a cross-roll rolling mill with a roll diameter of 160 mm and a roll speed of 5 m/min. The cross-roll angle (CRA) varied from 0° to 2.5°, 5° and 7.5° against TD in the RD-TD plane. Cross-roll rolling was conducted to a thickness reduction of 75% at 573 K. And then, the rolled Mg alloy sheets were annealed at 573 K for 30 min. The microstructures of the rolled samples were examined via optical microscopy (OM). The sample preparation for the measurement with OM consisted of grinding on SiC papers with 600, 800, 1000, and 2000 grit sizes, followed by mechanical polishing with 1 and 0.5 μm diamond paste and final polishing using colloidal silica. Additionally, the grain structure was revealed by subsequent etching using a solution of ethanol (100 ml), picric acid (5 g), acetic acid (5 ml) and water (10 ml). The average grain sizes were measured via the linear intercept method. To investigate mechanical properties, tensile test was carried out using the tensile specimens with tensile axes of 0°, 45° and 90° with respect to the RD. The specimens were strained by 15% at a constant cross-head speed of 1.0 × 10⁻³ m/s⁻¹.

3. Results and Discussion

The evolution of strains in the AZ31 samples cross-rolled with various CRAs was simulated with the commercial FEM package DEFORM™-3D.18) Figures 1(a) and (b) show the variations of effective strains ε_eff along the streamlines of
surface and center layers during cross-roll rolling in the AZ31 alloy sample. The effective strains $\varepsilon_{\text{eff}}$ were computed according to\(\textsuperscript{16,18}\)

$$\varepsilon_{\text{eff}} = \sqrt{\frac{2}{3}} \int (\varepsilon_{11}^2 + \varepsilon_{22}^2 + \varepsilon_{33}^2 + 2\varepsilon_{12}^2 + 2\varepsilon_{13}^2 + 2\varepsilon_{23}^2)^{1/2} \, \text{d}t$$ \hspace{1cm} (1)

In all the samples, higher effective strains are always obtained at the surface layer than at the center layer. This is because one of shear strain, $\varepsilon_{31}$, develops at the surface layer strongly. Increasing CRA, the one of the shear strain, $\varepsilon_{23}$, increases at the whole thickness layers. Then, the samples with higher CRA have much higher effective strains at the whole thickness layers. Since the other shear strain components exclusive of $\varepsilon_{23}$ are nearly zero at the center layer, the effect of $\varepsilon_{23}$ on effective strain is dominant. Accordingly, the difference in effective strains of samples with various CRAs is more notable at the center layer than at the surface layer.

Figure 2 shows microstructures after rolling and subsequent annealing at 573 K for 30 min CRA = (a), (b) 0°, (c), (d) 2.5°, (e), (f) 5° and (g), (h) 7.5°: ((a), (c), (e), (g) before annealing; (b), (d), (f), (h) after annealing at 573 K for 30 min). At a CRA of 0° before annealing, many twins inside large grains were found on center layer (Fig. 2(a)). Dynamic recrystallized (DRX) grains were not observed. With increasing CRA from 2.5° to 7.5°, many twins inside small grains were found on center layer. On the other hand, after annealing at 573 K for 30 min, with increasing CRA from 0° to 7.5° the center layers showed a behavior similar to all specimens. A number of twins were completely removed as shown in Figs. 2(b), (d), (f), (h). Moreover, dynamic recrystallized (DRX) grains were observed.

In Fig. 3, the average grain sizes measured at the surface and center layers of the rolled at different CRAs after annealing at 573 K for 30 min. With the increase in CRAs, the average grain sizes decreased at the whole thickness layers. Additionally, declination of average grain size with respect to CRA is notable at center layer. It is for the reason that the many DRX grains produced by the high plastic energy. Note that with increasing CRA the deviation of grain size between center and surface layers reduced. Since high accumulative energy can provide more nucleation sites during recrystallization, grain refinement can be achieved with increasing the accumulative energy. As mentioned in the result of FEM simulation, with increasing CRA the different in effective strains at center and surface layers decreases. Consequently, with increasing CRA the decrease of difference in average grain size at center and surface layers is attributed to the reduction of dissimilarity in the effective strains.

In order to improve the in-plane formability of metal sheet, it is necessary to increase $r$-value.\(\textsuperscript{19}\) Figure 4 shows the evolution of the $r$-values of the recrystallized samples. The samples rolled with higher CRA have much higher $r$-values at almost all angles. For quantitative comparison, the average value $\bar{r}$ is calculated by:

$$\bar{r} = \frac{r_0 + r_{45} + r_90}{4}$$ \hspace{1cm} (2)

where $r_0$, $r_{45}$ and $r_{90}$ is the $r$-value in which the angle between rolling direction and tensile direction is 0°, 45° and 90°, respectively. The average $r$-values of the samples rolled with CRA = 0°, 2.5°, 5° and 7.5° are 1.65, 2.14, 2.53 and 2.78, respectively. With increasing CRA, the $\bar{r}$-values gradually increase. In order to obtain higher in-plane formability during deep-drawing, it is essential for the reduction of $\Delta r$-value as well as the increase in $\bar{r}$-value. $\Delta r$-value means the variation of the $r$-value in the sheet plane and is defined as:

$$\Delta r = \frac{(r_0 - 2 \cdot r_{45} + r_{90})}{2}$$ \hspace{1cm} (3)

The $\Delta r$-values of the samples rolled with CRA = 0°, 2.5°, 5° and 7.5° are 0.62, 0.14, 0.06 and 0.1, respectively. In comparison with the conventionally rolled sample, i.e., CRA = 0°, the $\Delta r$-values of the cross-roll rolled samples dramatically decrease. Accordingly, increasing CRA during cross-roll rolling, much higher in-plane formability can be obtained.

The mechanical properties including ultimate tensile strength (UTS), 0.2% proof stress (YS), fracture elongation (FE), uniform elongation (UE), and strain hardening exponent value ($n$-value) of the annealed sheets rolled at different temperatures are summarized in Table 1. UTS and YS hardly vary with respect to CRA. However, FE, UE and $n$-value of the cross-roll rolled samples improve outstandingly in comparison with those of the conventional rolled sample, CRA = 0°. As a result, while the increase in CRA can scarcely affect on the strength of samples it can be improve the formability of samples remarkably.
Fig. 2 The microstructure of the cross-roll rolled AZ31 alloy samples at center layer: CRA = (a), (b) 0°, (c), (d) 2.5°, (e), (f) 5° and (g), (h) 7.5°: (a), (c), (e), (g) before annealing; (b), (d), (f), (h) after annealing at 573 K for 30 min.

Fig. 3 The average grain sizes measured at the surface and center layers of the rolled at different CRAs.

Fig. 4 The average $r$-value of the rolled AZ31 Mg alloy sheets at different CRAs.
4. Conclusions

Rolling was conducted using a cross-roll rolling mill in which the roll axes were tilted 0°, 2.5°, 5° and 7.5° away from the transverse direction. The effective strains during cross-roll rolling were simulated by three-dimensional FEM. Increasing the cross-roll angle the through-thickness variation of effective strains decreases extremely. Microstructures observed in recrystallization annealed samples display that the uniform and fine grain size was obtained at whole thickness layers with increasing the cross-roll angle from 0° to 7.5°. The result of tensile test reveals that while the increase in cross-roll angle can hardly affect on the strength of samples it can improve the formability of samples outstandingly.

REFERENCES


Table 1 Results of the tensile tests carried out in the tensile specimens with the tensile axes lying 0°, 45° and 90° with respect to the RD.

<table>
<thead>
<tr>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
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<th>UE (%)</th>
<th>n-value</th>
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<tr>
<td>CRR 0°</td>
<td>271 260 258</td>
<td>199 184 174</td>
<td>20.3 24.0 18.2</td>
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<td>195 189 182</td>
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