Texture and Formability of Heat-treatable Magnesium Alloy Sheets Processed by Differential Speed Rolling

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The differential speed rolling (DSR) process has been carried out on a heat-treatable AZ61 magnesium alloy at different rotation speed ratios (RSR). Compared with the normal symmetrically rolled sheet without an inclination of basal pole, the sheets DSR-processed at the RSRs of 1.17 and 1.36 exhibit the inclination of basal pole toward the rolling direction at about 5º and 10º, respectively, while the microstructures show approximately the same grain size of 7 µm. Increasing the RSR leads to the decreases in 0.2% proof stress (YS) and r-value as well as the increases in uniform elongation and n-value. For the sheet DSR-processed at the RSR of 1.36, the ultimate tensile strength (UTS), the YS, the fracture elongation (FE) and the Erichsen value (IE) are 313 MPa, 182 MPa, 24.3% and 4.7, respectively. This IE is higher than that (4.1) of the normal-rolled sheet. The improvement of the stretch formability can be attributable to the texture favored for the basal slip during deformation. After aging treatment, the UTS and the YS further increase to 336 MPa and 208 MPa, respectively, accompanied with a decrease in the FE.

Key words: Magnesium alloys; Asymmetric rolling; Texture; Mechanical properties; Formability

1. INTRODUCTION
Magnesium (Mg) wrought alloys have a great potential as light-weight structural materials substituting for steel and aluminum (Al) parts in automotive and electronic industries due to their excellent properties such as low density, high specific strength, good damping characteristics, good electromagnetic shielding capability, easiness of recycling and abundance of resources [1]. However, normal symmetric rolling generally gives rise to a strong basal texture for the Mg alloys [2]. This induces a high normal anisotropy in sheet and increases the difficulty in deformation accompanied with thickness reduction, and consequently leads to a very limited formability at ambient temperatures.

The deformation capability of the Mg alloy sheets is strongly affected by the texture [3,4]. In recent years, differential speed rolling (DSR) has been utilized for enhancing deformation capability of the Mg alloy sheets by microstructure modifications [5-7]. The DSR is a process carried out at different rotation speeds for upper and lower rolls so that intense shear deformation can be introduced throughout the sheet thickness and thus may lead to a weakened basal texture and/or an inclination of basal pole [8,9]. However, the DSR-processed Mg alloy sheets reported in the literature are mainly limited to the AZ31 alloy. In general, the AZ31 alloy exhibits a better ductility but a lower mechanical strength compared with the other AZ series alloys such as AZ61, AZ80 and AZ91 with higher Al contents. This limits the applications as a structural component requiring a high strength. The tensile strength of the AZ61 alloy is comparable to the 5000 and 6000 series Al alloys, which have been applied to auto body panels [10]. In addition, it is possible to improve the mechanical strength of the AZ61 alloy further by subsequent artificial aging treatment, which induces precipitation strengthening due to precipitation of β-phase (Mg17Al12).

In this study, the DSR process was carried out on the AZ61 alloy in order to achieve the Mg alloy sheet with a combination of high strength and superior formability, and the influences of the rotation speed ratio (RSR) on microstructure, texture, mechanical properties and stretch formability were systematically investigated.

2. EXPERIMENTAL PROCEDURE
The starting billets were cut from the commercial hot-extruded AZ61 (Mg-6.9Al-0.5Zn-0.2Mn in wt.%) alloy plates with a thickness of 5 mm. The as-received material consists of equiaxial recrystallized grains with an average grain size of 13 µm. The rolling was conducted at the RSRs of 1 (i.e. normal rolling), 1.17 and 1.36 without lubrication on roll and billet surfaces. The billets were rolled from 5 mm to 1 mm in thickness.
by 4 passes with a large thickness reduction per pass of 33% and the total thickness reduction was 80%. The billets for rolling were heated to a high temperature of 703 K in order to avoid the precipitation of Mg17Al12 during rolling and both rolls were heated to 573 K using heat elements embedded inside the rolls. The sheet was rotated and reversed after each pass so that the shear strain was introduced unidirectionally throughout the rolling. All as-rolled sheets were subjected to optical microscopic observation, x-ray texture analysis, microhardness measurement, tensile test and Erichsen test at room temperature. Hereafter, RD, TD and ND denote the rolling, transverse and normal directions of sheet, respectively.

The (0002) pole figure was measured at the mid-plane of sheet by the Schulz reflection method. The tensile tests were conducted using an Instron universal testing machine with an extensometer at the angles of 0º (RD), 45º and 90º (TD) between the tensile direction and the RD. The average values of the mechanical properties were given from the values of the three tensile directions by the following expression:

\[ \bar{X} = \frac{X_{RD} + 2X_{45º} + X_{TD}}{4} \]

The circular blanks with a diameter of 50 mm were used for the Erichsen tests for evaluating the stretch formability. The Erichsen tests were conducted using a hemispherical punch with a diameter of 20 mm. The punch speed was set as 5 mm/min and the blank holder force was set as 10 kN. The graphite grease was used as a lubricant for the Erichsen tests. The Erichsen value (IE) was measured as the punch stroke at fracture initiation.

3. RESULTS AND DISCUSSION

The microstructures of the sheets rolled at different RSRs are shown in Fig. 1. The as-rolled sheets exhibit the well-equiaxed grains indicating the occurrence of dynamic recrystallization due to the high rolling temperature. All sheets exhibit approximately the same grain size of 7 µm, which is smaller than that (13 µm) of the as-received hot-extruded plate. Almost no Mg17Al12 precipitates can be observed, indicating that most of the Al atoms dissolve in the matrix.

The (0002) pole figures of the sheets rolled at different RSRs are shown in Fig. 2. The basal texture intensities are approximately the same while the distributions of {0001} orientation are different among the sheets. The normal-rolled sheet exhibits the spread of {0001} orientation toward the RD without an inclination of basal pole. In contrast, the basal pole inclines toward the RD for the DSR-processed sheets. The inclination angles of the basal pole are 5º and 10º for the sheets DSR-processed at the RSRs of 1.17 and 1.36, respectively. In addition, the spread of the basal pole in the TD is also slightly wider and tends to exhibit a roughly circle-shaped distribution of {0001} orientation compared with the normal-rolled sheet. The inclination of the basal pole can be attributable to the intense shear deformation throughout the sheet thickness during the DSR process.

The changes in average values of the ultimate tensile strength (UTS), the 0.2% proof stress (YS), the fracture elongation (FE) and the uniform elongation (UE), the Lankford values (r-value), the strain hardening exponent (n-value) and the IE as a function of RSR are shown in Fig. 3. All sheets exhibit approximately the same UTS of 313-318 MPa while the YS slightly decreases from 191 MPa to 182 MPa with increasing the RSR from 1 to 1.36. The decrease in the YS can be attributable to the texture effect considering the same grain size. The inclination of basal pole may lead to a larger Schmid factor of the basal slip due to the inclination of the basal planes from the rolling plane and thus exerts an effect on the decrease in the YS. The FE also slightly increases from 23.0% to 24.3% and it is originated from the increase in the UE, which increases from 18.4% to 19.7% with increasing the RSR. The r-value decreases from 2.06 to 1.71 and the n-value increases from 0.239 to 0.256 simultaneously. The IEs are 4.1, 4.4 and 4.7 for the sheets rolled at the RSRs of 1, 1.17 and 1.36, respectively, exhibiting the enhancement...
of the stretch formability with increasing the RSR. Under a biaxial tension stress state of the stretch forming, the thickness strain is most necessary for forming. The enhancement of the stretch formability can be attributed to the decrease in the \( r \)-value and the increase in the \( n \)-value, which enhances the capability of sheet thinning. It is known that the \( r \)-value is strongly related to the texture. The Mg alloy sheet with a very strong basal texture unfavorable for the basal slip during tensile deformation generally exhibits a large \( r \)-value, because pyramidal \(<c+a>\) slip with the largest critical resolved shear stress (CRSS) in the slip systems is needed for generating the thickness strain while the width strain can be generated by prismatic \(<a>\) slip [11,12]. A tilted basal pole increases the Schmid factor of basal slip with the lowest CRSS and is favored for the basal slip during deformation. This promotes the strain in the thickness direction and in turn decreases the \( r \)-value. In addition, the inclination of the basal pole may also increase the \( n \)-value [13]. Therefore, the enhancement of the stretch formability of the DSR-processed sheet is originated from the texture effect. Compared with the hot-rolled AZ31B alloy sheets generally exhibiting the IE of 3-5 and the UTS of 250-260 MPa [3,7,14], the AZ61 alloy sheet DSR-processed at the RSR of 1.36 exhibits a comparable IE of 4.7 but a much higher UTS of 313 MPa. This high strength results from the solid solution strengthening due to the dissolution of Al in the matrix.

The change in Vickers microhardness of the sheet DSR-processed at the RSR of 1.36 during the aging treatment at 448 K is shown in Fig. 4a. The microhardness increases with the aging time and reaches the peak at about 48 h. The Vickers hardnesses for the as-rolled and peak-aged conditions are 71 and 85, respectively. The nominal stress-strain curves of the DSR-processed sheets at the as-rolled and peak-aged conditions in the tensile directions of RD, 45º and TD are shown in Fig. 4b. After aging treatment, the UTS enhances from 313 to 336 MPa and the YS also improves from 182 to 208 MPa by 23 and 26 MPa, respectively, due to the precipitation of \( \text{Mg}_17\text{Al}_{12} \). However, the FE, the UE and the \( n \)-value decrease from 24.3% to 21.0%, from 19.7% to 15.2%, and from 0.256 to 0.189, respectively, which would result in a deterioration in stretch formability. It is suggested that the precipitates increase the flow stress and thus activate the dynamic recovery during deformation, which results in the decrease in work hardening rate. Therefore, the aging treatment should be conducted after the shape forming. Anyway, a further improvement in mechanical strength can be achieved by the aging treatment for the AZ61 alloy while this effect is weak for the AZ31 alloy.

4. CONCLUSIONS
(1) The DSR-processed sheets exhibit approximately the same grain size compared with the normal-rolled sheet while the inclination of basal pole enhances with increasing the RSR.
(2) The sheet DSR-processed at the RSR of 1.36 in the as-rolled condition exhibits a combination of high strength (UTS: 313 MPa) and high ductility (FE: 24.3%). The IE also improves from 4.1 to 4.7 compared with the normal-rolled sheet. The improvement in the stretch formability can be attributed to the favored texture for the basal slip during deformation.
(3) The aging treatment improves the mechanical strength further while it decreases the work-hardening capability and the tensile elongation.

REFERENCES
Fig. 3. Changes in average values of (a) the UTS and the YS, (b) the FE and the UE, (c) the $r$-value and the $n$-value, and (d) the IE as a function of RSR. The blanks of the normal-rolled sheet and the sheet DSR-processed at the RSR of 1.36 after the Erichsen tests are shown in the inset of (d).

Fig. 4. (a) Vickers microhardness of the sheet DSR-processed at the RSR of 1.36 as a function of aging time at 448 K starting from the as-rolled condition. (b) Nominal stress-strain curves of the DSR-processed sheets in the as-rolled and aged at 448 K for 18 h conditions in the tensile directions of RD, 45º and TD.