EFFECT OF THERMAL PROCESSING ON THE FORMABILITY OF TTMP AZ61L SHEET

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Abstract

The application of magnesium alloy sheet requires a greater understanding of microstructure and texture to control formability. In this study, the influence of thermal processing history on the microstructure and tensile deformation behavior of Thixomolded and Thermomechanically Processed (TTMP) AZ61L sheet is examined. Microstructural analysis indicates that the as-rolled sheet is only partially recrystallized. Significant increases in ductility with only moderate reductions in tensile strength are produced with thermal treatments above 285°C. Specimens with the most improved ductility are shown to have undergone static recrystallization. The recrystallized sheet has an average r-value and a planar anisotropy r-value of 1.09 and 0.12 respectively. The increased ductility and decreased tensile anisotropy is ascribed to reduction in basal texture that occurs during the recrystallization process, as by X-Ray and Electron Backscatter Diffraction.

Introduction

Magnesium is the lightest structural metal; therefore the automotive, personal electronic, and medical industries can benefit from the use of magnesium alloy sheet for weight reduction. However due to its hexagonal crystal structure, magnesium has a limited number of slip systems at room temperature, which leads to poor formability. The most favorable deformation mode is basal slip, which leads to a strong basal, or near basal texture in rolled Mg alloy sheet [1]. Reduction of this basal texture is necessary to improve formability of Mg sheets.

This experiment builds on our previous work, addressing the challenge of producing high strength, high ductility Mg-sheet with good formability. The fine grain structure of Thixomolded Mg-alloys is advantageous for thermomechanical processing to finer grain sizes [2]. In addition, post-processing annealing of TTMP AZ61L has shown to alleviate the near-basal texture imparted by rolling [3]. The objective of this study is to address the relationship between texture and planar anisotropy in TTMP AZ61L.

Experimental

Thixomolded AZ61L (Table I) plates of dimensions of 200 mm x 200 mm x 3 mm were preheated and then warm-rolled with a roll temperature near 200°C. The resulting thickness was 1.8 mm, a thickness reduction of 40%. Dogbone tensile specimens with a gauge length of 25.45 mm and cross section of 6.35 mm x 1.8 mm were machined from the sheets with the tensile axis at 0°, 45°, or 90° from the rolling direction. Room temperature tensile tests were performed with a displacement rate of 0.60 mm/min. Three specimens were used for each condition. An extensonometer was used to measure tensile elongation. Samples used for r-value measurements were strained to 12%. Vickers hardness measurements were made with a Clark Microhardness tester with a dwell time of 15 s and a 200 g load.

XRD samples were prepared by grinding to 1200 grit SiC paper. SEM samples were prepared by polishing to 1 µm diamond paste and then etching for 10 s at room temperature in a 1:9 solution of o-phosphoric acid in ethanol. Electron Backscatter Diffraction (EBSD) specimens were prepared by polishing to 1 µm diamond paste followed by ion polishing in a Gatan PIPS. EBSD examination was conducted with a Philips XL30 FEG equipped with a
<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Mg</th>
</tr>
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<tr>
<td></td>
<td>6.5</td>
<td>0.46</td>
<td>0.14</td>
<td>0.01</td>
<td>0.003</td>
<td>bal.</td>
</tr>
</tbody>
</table>

**Figure 1**: Static recrystallization model based on JMAK theory. The Avrami exponent, $n$, was found to be 0.94. Experimental values were determined by plotting the change in hardness from the as-rolled condition ($H_{AR}$) over the total change in hardness, where $H_{min}$ represents the final hardness of fully recrystallized material. Partial basal pole figures (to 75°) are presented to highlight the conditions selected for this study. The intensity of the basal peaks decreases and the distribution broadens during annealing.

TexSEM Laboratories OIM system. A Rigaku rotating anode XRD system was used to make incomplete XRD pole figure measurements to 75°.

**Results**

Recrystallization
Victors hardness measurements of TTMP AZ61L sheet with 10 minute annealing treatments up to 340 °C indicate that static recrystallization is occurring during the annealing process (Figure 1). The kinetics of this process match well with those of the Johnson-Mehl-Avrami-Kolmogorov (JMAK) theory [4]. To explore the relationship between texture and anisotropy during tensile deformation, two annealing temperatures were chosen, 255°C and 285°C, representing material at the initiation and near the end of the recrystallization process.

Microstructure
Figure 2 illustrates the distribution of the brighter $\beta$-phase for the three conditions. The $\beta$-particles for all conditions have a mean circular diameter of 0.4 $\mu$m or less. Very fine needle-like precipitates are seen in the as-rolled material and the material annealed at 255°C. The microstructure of the material annealed at 285°C differs from that produced by the 255°C in that the boundaries of recrystallized grains are now visible (Figure 2). It is clear that multiple recrystallized grains are found within the bounds of the $\beta$ network. After the 285°C anneal, the fine needle-like precipitates have completely dissociated into the matrix.

The as-rolled material consists of recrystallized regions with a near-basal texture and deformed $\alpha$-Mg grains (Figure 3). EBSD characterization on the as-rolled material is challenging due to the residual deformation; less than 20% of the points index as Mg with a confidence index (CI) greater than 0.05. The inverse pole figure maps indicate that only partial recrystallization has occurred after annealing at 255°C. The fraction of points indexed as Mg with a CI
Figure 2: Microstructure of the as-rolled condition, sample annealed at 255 °C for 10 minutes, and sample annealed at 285 °C for 10 minutes. β-Mg₁₇Al₁₂, the brighter phase, is heterogeneously distributed. Grain boundaries are evident after the 285 °C anneal. Multiple recrystallized grains are found within the bounds of the visible β phase.

Figure 3: Inverse pole figure maps of the as-rolled condition, sample annealed at 255 °C for 10 minutes, and sample annealed at 285 °C for 10 minutes. The as-rolled material is highly deformed; undeformed grains have a near-basal orientation. The initiation of recrystallization is evident after annealing at 255 °C. After annealing at 285 °C for 10 minutes the material is fully recrystallized.

greater than 0.05 is 20%. After annealing at 285 °C for 10 minutes the material is completely recrystallized, with an average equivalent circular grain diameter of 4.3 µm. More than 45% of points indexed as Mg with a CI greater than 0.05.

Crystallographic Texture

XRD pole figure analysis was conducted on the sheet cross section in order to be able to capture texture information that would fall at angles greater than 75° in the planar orientation. XRD pole figures (Figure 1) reveal that the as-rolled sheet has a near basal texture in the plane of the sheet, with double peaks located ~ 20° from the basal direction. This texture is weakened slightly after the 255 °C annealing treatment, but the location of the poles is unchanged. The basal texture is greatly diminished after annealing at 285 °C for 10 minutes and the peaks tilt further away from the basal pole, to near 45°. The texture is elongated along the TD after rolling, as indicated by the 1010 pole figures (Figure 4). This texture broadens with increasing annealing temperature.
Figure 4: Partial (to 75°) 10\bar{1}0 pole figures maps of the as-rolled condition, sample annealed at 255°C for 10 minutes, and sample annealed at 285°C for 10 minutes. The corresponding 0002 pole figures can be found in Figure 1. Pole figures were taken along the rolling direction. In the un-recrystallized material elongation along the TD direction is evident.

Figure 5: Stress-strain curves typical tensile specimen. In the un-recrystallized materials, the UTS is significantly higher when the tensile axis is along the RD. The behavior is isotropic in the sample annealed at 285°C.

Mechanical Properties

The uniaxial tensile behavior of the TTMP AZ61L sheet in three orientations with respect to the rolling direction is summarized in Figure 5 and Table II. Strength decreases, and elongation increases, with increasing annealing temperature. The as-rolled sheet has a maximum elongation of 13.1% and an ultimate tensile strength of 362.9 MPa along the rolling direction. Material annealed at 285°C shows an improvement in elongation, to 21.5%, and a drop in yield and ultimate tensile strengths of ∼30 MPa. For the as-rolled and 255°C anneal, strength is significantly higher along the rolling direction. Strength is comparable in the two other orientations. After the high temperature anneal, strength becomes more isotropic.

The Lankford coefficient, or r-value, is commonly used to determine press formability of steel and Al alloys sheets. The r-values of TTMP AZ61L were calculated to study changes in deformation anisotropy. The r-value ($r$), the mean r-value ($\bar{r}$) and the planar anisotropy of r-value ($\Delta r$) are given by [5]:

$$ r = \epsilon_w/\epsilon_t $$  

$$ \bar{r} = |r_0 + 2 * r_{45} + r_{90}|/4 $$  

$$ \Delta r = |r_0 - 2 * r_{45} + r_{90}|/2 $$

The r-values for the TTMP AZ61L sheet material are all quite low for a Mg sheet alloy, even in the as-rolled sheet. Mean r-values of 3 or more are typical in AZ-series alloys [6–9]. The planar anisotropy r-value for the 285°C anneal is only 0.1, with zero meaning the material is perfectly isotropic.
Table II: Tensile properties of TTMP AZ61L sheet. Annealing treatments were 10 minutes in duration. Samples strained to 12% were used for determination of the Lankford value.

<table>
<thead>
<tr>
<th>Anneal</th>
<th>Angle</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>El (%)</th>
<th>r</th>
<th>¯r</th>
<th>Δr</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-Rolled</td>
<td>0</td>
<td>297.2 ± 40.2</td>
<td>362.9 ± 3.4</td>
<td>13.1 ± 0.3</td>
<td>1.48</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>45</td>
<td>271.7 ± 42.7</td>
<td>334.6 ± 2.3</td>
<td>15.0 ± 3.2</td>
<td>1.59</td>
<td>1.44</td>
<td>0.30</td>
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<tr>
<td></td>
<td>90</td>
<td>243.2 ± 24.5</td>
<td>338 ± 1.2</td>
<td>14.8 ± 2.7</td>
<td>1.10</td>
<td></td>
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</tr>
<tr>
<td>255 °C</td>
<td>0</td>
<td>251.9 ± 23.9</td>
<td>336.3 ± 1.6</td>
<td>16.1 ± 0.1</td>
<td>1.00</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>45</td>
<td>224.4 ± 22.8</td>
<td>312.1 ± 4.1</td>
<td>16.9 ± 2.6</td>
<td>1.20</td>
<td>1.12</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>204.7 ± 19.8</td>
<td>322.4 ± 13.4</td>
<td>14.4 ± 7.1</td>
<td>1.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>285 °C</td>
<td>0</td>
<td>206.5 ± 7.9</td>
<td>306.5 ± 1.2</td>
<td>21.5 ± 1.8</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>197.3 ± 9.1</td>
<td>299.5 ± 3.0</td>
<td>19.1 ± 2.0</td>
<td>1.14</td>
<td>1.09</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>202.4 ± 2.8</td>
<td>301.9 ± 5.2</td>
<td>17.5 ± 3.5</td>
<td>1.09</td>
<td></td>
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</table>

Discussion

Our results indicate that static annealing of TTMP AZ61L sheet leads to a reduction in basal texture that results in an improvement in elongation and a reduction in planar anisotropy. The texture of the as-rolled sheet is weak, with a maximum basal pole figure intensity of 3.1 M.R.D., with values near 10 being reported in conventional AZ-series alloys [7, 10–12]. The average r-value for the as-rolled material, 1.44, is similarly low, with values near 3 being typical [7, 10–13]. The refined $\beta$-Mg$_{17}$Al$_{12}$ phase in our material may be responsible for this low texture and associated low deformation anisotropy. Li et al have explored the influence of the $\beta$-Mg$_{17}$Al$_{12}$ phase on texture evolution during compression and found that a sufficient amount of $\beta$-phase promoted dynamic recrystallization during deformation [14].

The basal pole figure of the TTMP AZ61L is unique among AZ-series alloys. The split of the basal pole in the RD is commonly observed [9, 10, 15]; however, an elongation in the TD is more frequently reported in RE containing Mg-alloys [16, 17]. This difference may be a result of the $\beta$-Mg$_{17}$Al$_{12}$ phase present in the TTMP AZ61L sheet; reports on deformation anisotropy in AZ-series alloys are often of AZ31 or solution treated materials. The elongation along the TD is important when considering the anisotropy in the tensile behavior.

The UTS is highest when the tensile axis is parallel to the rolling axis for the as-rolled and 255 °C anneal conditions, and lowest when the tensile axis is at 45° from the RD. These results can be put in context with the basal pole figures. If all grains in a sheet were oriented with their c-axis parallel to the sheet normal but with the (1120) directions being randomly distributed in the RD-TD plane, there would be no anisotropy in the plane of the sheet. The tilt of the basal planes toward the RD decreases the angle between the tensile axis and the [0002] plane normal, which decreases the activity of basal slip and thus less strain is able to be accommodated before fracture. The elongation along the TD in the basal pole figure has the same impact when the tensile axis is along the TD, however as the intensity in the TD is weaker compared to that in the RD, the effect is weaker. There is less spread in intensity at 45° from the RD; this orientation is most favorably oriented for basal slip system and thus this direction exhibits the lowest UTS and highest elongation before fracture. The texture is less intense and more isotropic around the basal pole after the 285 °C anneal, and thus the tensile behavior exhibits decreased anisotropy.

The $\beta$-Mg$_{17}$Al$_{12}$ phase in AZ series Mg alloys may allow for texture reduction by providing numerous sites for nucleation of randomly oriented grains through the mechanism of particle stimulated nucleation [14]. Either micron-sized $\beta$ particles or regions with a high density of sub-micron $\beta$ particles can serve as nucleation sites. Partially dynamically recrystallized Mg alloy sheet will have a reduced basal texture due to particle stimulated nucleation [14]. In partially recrystallized sheet, further texture reduction can be elicited as the recrystallized $\alpha$-Mg grains consume the deformed material in post-processing annealing. $\beta$ particles also serve to pin grain boundaries and thus help retain a fine grained material. Future work will explore the impact of the $\beta$-particle size, volume fraction, and distribution on the recrystallization and grain growth kinetics.
Conclusions

1. The microstructures, textures, and tensile properties of TTMP AZ61L sheet have been characterized following rolling and subsequent annealing at either 255°C or 285°C for 10 minutes.

2. The sheet is partially recrystallized during rolling. After 10 minutes at 255°C static recrystallization has begun. Static recrystallization is complete after 10 minutes at 285°C.

3. The as-rolled sheet has a weak near-basal texture. After complete static recrystallization the basal texture of the sheet is appreciably reduced. A small change in the texture intensity is seen between the as-rolled material and that annealed at 255°C for 10 minutes.

4. The as-rolled sheet has a low average r-value for Mg-alloy sheet. Anisotropy in uniaxial tensile tests is further alleviated by the 285°C annealing treatment.

5. Static recrystallization leads to a reduction of texture which produces an isotropically deformable AZ61L sheet with a yield strength of 201.8 ± 7.5 MPa an ultimate tensile strength of 302.6 ± 4.4 MPa and elongation of 19.2 ± 2.9 %.

Acknowledgements

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References