Grain Size Dependence of Yield Strength in Randomly Textured Mg-Al-Zn Alloy

Y. N. Wang$^{1,2}$ and J. C. Huang$^{1,*}$

$^1$Institute of Materials Science and Engineering: Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Kaohsiung, Taiwan 804, R.O. China

$^2$Institute of Materials Science and Engineering; Center for Nanoscience and Nanotechnology, Dalian University of Technology, Dalian 116024, P.R. China

The randomly textured Mg-Al-Zn alloy processed by electron beam welding typically exhibits clear grain size dependence of yield strength according to the Hall-Petch relationship: $\sigma_0 = 62 + 202d^{-1/2}$. The Schmid factor for the basal slip system was deduced to be around 0.031 in the randomly textured Mg alloys. The $\sigma_0$ in the Hall-Petch equation was theoretically calculated to be $\sim 65$ MPa, which is reasonably consistent with the experimental data of $\sim 62$ MPa. [doi:10.2320/matertrans.48.184]

(Received October 18, 2006; Accepted December 1, 2006; Published January 25, 2007)

Keywords: magnesium alloy, random texture, Schmid factor, grain size dependence

1. Introduction

The previous report has indicated that the grain size strengthening efficiency in Mg alloys is much higher than that in Al and other alloys.$^1$ This means that grain refinement will be more beneficial when applied on magnesium alloys. Thus, great efforts focusing on the microstructural modifications of magnesium alloys have been made in order to enhance and control the mechanical performances.$^2$–$^3$)

On the other hand, the critical resolved shear stress (CRSS) of the basal slip system ($\sim 0.5$ MPa) in pure Mg is lower than that of non-basal slip systems (usually more than 40 MPa).$^1$)

As a result, when the wrought magnesium alloys have strong texture in the microstructures, their mechanical properties, especially the yield strength (YS), would be significantly affected by the resulting textures in addition to the grain size.$^4$–$^7$,11,12$)

Recently, there are a large number of reports on the relationship between the grain size and mechanical properties of magnesium alloys based on the Hall-Petch relationship.$^7$,15–18$) It can be seen that there exists apparent distinction for the grain size dependence of YS in the same alloy subjected to different thermo-mechanical processes. This effect is generally considered to be contributed by the texture influence.

Generally, for the strongly textured magnesium alloys, the entire texture can be approximately regarded as a mixture of an ideal texture component and a random texture component. So far, the qualitative explanation for the texture effect on YS was mainly based on an assumption that there is an ideal texture component in the textured magnesium alloys. In order to evaluate the contribution from texture to the grain size dependence of YS, it is necessary to quantitatively determine the grain size dependence of YS in a randomly oriented magnesium alloy. It is noticed that the strong texture can be easily produced in the magnesium alloys during various thermo-mechanical processes, including extrusion, rolling, friction stir process (FSP) and equal channel angular pressing (ECAP), $et$ $al$. Therefore, it is difficult to prepare the randomly textured magnesium alloy samples. Fortunately, it is found that the fine-grained microstructure with weak textures can be produced by electron beam welding (EBW) in the fusion zone (FZ) of EBW magnesium alloys, owing to the high solidification cooling rate inside the fusion zone.$^{19}$

In the present paper, the tensile specimens are sampled from the FZ of the EBW AZ31 samples in order to establish the grain size dependence of YS in the randomly textured AZ31 alloy. The results are used as a base to roughly evaluate the influence of texture on grain boundary strengthening in the textured magnesium alloys, which were subjected to various thermo-mechanical processes.

2. Experimental Method

The chemical composition of the as-received AZ31B billet is Mg-3.02%Al-1.01%Zn-0.30%Mn (in mass percent). The as-received plate of 30 mm in thickness was autogenously bead-on-plate welded with the Torvac CVE63B electron-beam welding system in vacuum at around $1 \times 10^{-2}$ Pa. The electron-beam power of $1925$ W (voltage of $55$ kV and current of $35$ mA) and the weld speed of $20$ mm/s were applied. The cooling rate in the FZ is theoretically calculated to be $\sim 3000$ C/s. The detailed descriptions of the experiments can be found elsewhere.$^{19}$ Furthermore, the as-EBWed samples was subjected to annealing (denoted as the annealed sample) at $350$ C for various time durations, resulting in various grain sizes in order to examine the effect of grain size on YS.

Basic characterizations in terms of microstructure, FZ aspect ratio and possible porosity were examined by optical microscopy (OM) and scanning electron microscopy (SEM). The texture was determined the X-ray diffraction (XRD) patterns and pole figures. The grain size was analyzed by the Optimas image software on OM photographs taken at different magnifications. The tensile samples were cut from the FZ of the welded plates along the welding direction (WD), normal direction (ND) and transverse direction (TD), as depicted in Fig. 1.

All of the tensile specimens with 5.5 mm in gage length, 3 mm in width and 2 mm in thickness were prepared using electrical discharge machining. The tensile direction was
aligned parallel to the welding direction. Tensile tests were conducted using the Instron 5582 universal testing machine with an initial strain rate of $1 \times 10^{-3}$ s$^{-1}$ at room temperature.

3. Results and Discussion

Figure 2(a) shows the typical fine-grained structures of the EBW AZ31 sample. The average grain size is around 8 µm. The grain shape observed from different cross-sectional planes is confirmed to be the equiaxed type. During annealing, the normal grain growth takes place, and the grain size increases with increasing annealing time. The summary of grain size evolution in the annealed samples is listed in Table 1.

Figure 3 shows the XRD patterns for the longitudinal and transverse section in the annealed sample (350°C/120 min). The three peaks in the range of 30–40° from the low-angle side correspond to the prismatic (1010), basal (0002), and pyramidal (1011) planes, respectively. It can be seen that the relative X-ray intensities in the longitudinal and the transverse sections exhibit no pronounced difference among the three peaks. This indicates that the texture distribution in the annealed sample is reasonably homogeneous and nearly random.

The results of tensile tests at room temperature in the annealed samples are also summarized in Table 1. It can be seen that the yield strength and ultimate tensile strength (UTS) as well as tensile elongation (El) increase with decreasing grain size for the present samples, exhibiting the positive grain size dependence of strength.

It is well known that twin deformation often occurs in Mg and its alloys at room temperature, especially, occurs more easily in Mg alloys with a large grain size.\(^{20,21}\) In the present samples with nearly random texture, the Schmid factors for all the slip and twinning systems are all nearly the same, irrespective of the loading direction. In this case, the yielding behavior is mostly dependent on the basal slip system owing to the lowest CRSS of the basal slip system among all slip systems.

Table 1 Summary of grain sizes and mechanical properties in the annealed AZ31 samples. YS: yield stress; UTS: ultimate tensile stress; El: tensile elongation.

<table>
<thead>
<tr>
<th>Annealing time, min</th>
<th>Grain size (µm)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>El (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>11</td>
<td>125</td>
<td>211</td>
<td>17.2</td>
</tr>
<tr>
<td>30</td>
<td>16</td>
<td>110</td>
<td>186</td>
<td>15.7</td>
</tr>
<tr>
<td>60</td>
<td>32</td>
<td>97</td>
<td>175</td>
<td>12.2</td>
</tr>
<tr>
<td>120</td>
<td>38</td>
<td>93</td>
<td>164</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic drawing showing the tensile sample extracted from the FZ of the EBW AZ31 alloy. The tensile loading direction is parallel to WD.

Fig. 2 OM micrographs of grain structures in (a) the EBW AZ31 sample; (b) the annealed sample subjected to deformation up to 1% strain.

Fig. 3 X-ray patterns of the as-annealed sample (350°C/120 min). Longitudinal and transverse scans are obtained from the planes, perpendicular to the TD and WD directions, respectively.
and twinning systems. In order to confirm this case, the microstructure of the tensile deformed AZ31 sample (~1% strain) with a maximum grain size of ~40 μm was examined. No evidence for twinning deformation was observed for the deformed sample, as shown in Fig. 2(b). It was reported that non-basal slip of (a) or (c + a) dislocations is an important deformation mechanism in magnesium alloy polycrystals, especially in fine-gained magnesium alloys (usually smaller than 10 μm) at room temperature, contributing relatively high elongations (generally ~15–25%). The operation of the non-basal slip systems usually occurred at the middle or final deformation stage, at which the high intragranular stress was brought out owing to the increasing interactions between grain boundaries with increasing strain, which results in the activation of non-basal slip dislocations. However, no evidence of non-basal slip deformation was found in the initial deformation stage, especially in the yielding stage. Therefore, it is suggested that the grain size dependence of yield stress is not associated with twinning, but dominated by the slip, especially by the basal slip.

The Schmid factor m is defined as

\[ m = \cos \chi \cos \lambda, \]

where \( \chi \) is the angle between the normal of the easiest (0002) slip plane and the stress axis, and \( \lambda \) is the angle between the slip direction (1120) and the stress axis.

Assuming that the stress axis is fixed on any one direction, for example, parallel to WD, then the pole of the basal slip plane of a grain in the stereographic projection is located on the P(\( \chi, \varphi \)), as shown in Fig. 4, where \( \chi \) and \( \varphi \) are the angles between the normal of the basal plane and stress axis, and TD, respectively. For a randomly textured Mg polycrystalline sample, the normal direction of the basal slip plane would continuously changes from 0 to \( \pi / 2 \) with regard to the stress axis, and from 0 to \( 2\pi \) with respect to TD, respectively.

For any value of \( \chi \), there exists an optimally oriented (1120) slip direction for a grain. This optimally oriented slip direction \( \lambda_{\text{opt}} \) is lying in the plane defined by the normal to the basal plane and stress axis, namely, the sum of the angle \( \chi \) and \( \lambda_{\text{opt}} \) equals \( \pi / 2 \). Therefore, the term of \( \lambda_{\text{opt}} \) can be expressed as

\[ \cos \lambda_{\text{opt}} = \cos(\pi / 2 - \chi) = \sin \chi. \]

Taking into account of the symmetry of the (1120) slip direction rotated up to \( \pm \pi / 6 \) about the c-axis of the optimally oriented grain, the average of the cosine function from \( -\pi / 6 \) to \( \pi / 6 \) can be weighted by the factor \( 3/\pi \), and obtained as

\[ \cos \lambda = (3/\pi) \sin \chi. \]

Therefore, the Schmid factor \( m \) as a function of \( \chi \) can be written as

\[ m(\chi) = (3/\pi) \cos \chi \sin \chi. \]  

(1)

Taking into account all possible grain orientations, \( i.e. \) the angle of \( \chi \) varying from 0 to \( \pi / 2 \), and the angle of \( \varphi \) varying from 0 to \( 2\pi \), the average Schmid factor for the basal slip system in randomly textured Mg alloy can be obtained as follows:

\[ m = \left( \frac{1}{\pi^2} \right) \left( \frac{2}{\pi} \int_0^{\pi/2} \frac{3}{\pi} \cos \chi \sin \chi \right) \approx 0.031. \]  

(2)

In general, the yield strength at room temperature depends on the grain size, according to the Hall-Petch relation, \( \sigma_{0.2} = \sigma_0 + Kd^{-1/2} \), where \( \sigma \) is the yield stress of a polycrystalline metal, \( \sigma_0 \) is the yield stress relating to materials of infinite grain size, which is similar to the single crystal, \( K \) is a constant representing the grain boundary as a obstacle to slip across the grain boundaries, and \( d \) is the grain size. In the present study, the experimental Hall-Petch relation is expressed as \( \sigma_{0.2} = 62 + 202d^{-1/2} \), namely, the \( \sigma_0 \) and \( K \) are 62 MPa and 202 MPa(\( \mu m \))^{-1/2}, respectively, in the present randomly textured AZ31 alloy, as shown in Fig. 5.

For a single crystal, the yield stress \( \sigma_{0.2} \) is given by

\[ \sigma_{0.2} = (1/m) \cdot \tau_{\text{CRSS}}, \]

where \( m \) is Schmid factor; \( \tau_{\text{CRSS}} \) is critical resolved shear stress. The previous studies\(^{14,26,27}\) indicated that the increment of the CRSS of Mg solid solutions by adding Zn element is much larger than that by adding Al element for the basal slip system at room temperature. The CRSS in Mg-1.0 mass%Zn alloy was around 1.5 MPa at room temperature. Taking into account of the effect of adding Al element on the CRSS of Mg-1.0 mass%Zn alloy, the CRSS of the present Mg-3.0 mas-
s% Al-1.0 mass% Zn alloy may be around 2 MPa. By taking 2 MPa as a CRSS of basal slip system in the present AZ31 Mg alloy, the theoretical $\sigma_0$ can be easily calculated to be $\approx 65$ MPa (with $m \approx 0.031$) from the above equation, which is in high accordance with the experimental result of $\approx 62$ MPa.

The grain size dependence of $K$, expresses a magnitude of the resistance of the grain boundaries as an obstacle to the slip across the grain boundaries. This resistance of the grain boundaries is related to the stress concentration originating from the dislocations pile-ups behind the grain boundaries. Furthermore, the stress concentration against the grain boundaries will operate the dislocation action of the neighboring grain. When the neighboring grain has a preferred orientation (here refer as soft orientation with high Schmid factor), the dislocations slip in the soft oriented grain will be more easily operated than that in the grain with non-preferred orientation (here refer as hard orientation with low Schmid factor). Thus, in the soft oriented grains, the stress multiplication in the next grain should be much lower, resulting in the low value of $K$ (smaller than the present value of 202 MPa($\mu m)^{-1/2}$). In contrast, the case for the hard oriented grains would lead to a high value of $K$ (larger than 202 MPa($\mu m)^{-1/2}$).

The above discussion is also supported by some reports.\textsuperscript{28,29} For example, in the as-ECAPed and annealed AZ31 samples having a similar texture with mostly (0002) plane tiled $\approx 45^\circ$ to the pressing direction, a clear grain size dependence of YS is exhibited as $\sigma_{02} = 30 + 170d^{-1/2}$ according to the Hall-Petch relation.\textsuperscript{28} In this case, the Schmid factor can be calculated to be $\approx 0.48$ from equation (1) where $\chi = 45^\circ$. The high Schmid factor ($\approx 0.48$) is responsible for the low $\sigma_0$ and $K$ of the Hall-Petch relation in the as-ECAPed samples, as compared to the present randomly textured AZ31 alloy.

For the as-rolled AZ31 samples having a similar strong (0002) basal texture, an evident grain size dependence of YS is expressed as $\sigma_{02} = 89 + 230d^{-1/2}$.\textsuperscript{29} In this case, the ideal Schmid factor is null from equation (1) where $\chi = 90^\circ$. The low Schmid factor is responsible for the high $\sigma_0$ and $K$ of the Hall-Petch relation in the as-rolled samples, as compared to the current randomly textured AZ31 alloy.

Generally speaking, there only exists a strong texture component in the thermo-mechanical processed Mg-based alloys. For example, the hot rolling or hot extrusion process generally gives rise to a strong basal texture in magnesium alloys. In this case, the entire texture in hot rolled or hot extruded magnesium alloys can be regarded as a mixture of a basal texture component and a random texture component. Since the intensity of the resulting basal texture is also a function of rolling/extrusion temperature and reduction ratio, the relative volume fractions for the basal and random textures may be varied accordingly. Assuming the volume fraction of the basal texture component is determined, then, the effective (or actual) Schmid factor is expressed by $m = m_{\text{bas}} + m_{\text{ran}}(1 - V_f)$, where $V_f$ is the volume fraction of the basal texture component; $m_{\text{bas}}$ and $m_{\text{ran}}$ are the Schmid factors related to the basal texture and random texture components, respectively. Because $m_{\text{bas}}$ is equal to zero, then, the above equation can be written as $m = m_{\text{ran}}(1 - V_f)$. Table 2 lists the relationship between the volume fractions of basal texture (basal texture intensity) and the effective Schmid factor, as well as the theoretical $\sigma_0$ in the basal textured AZ31 alloy. It can be seen from Table 2 that the effective Schmid factor decreases with increasing volume fraction of the basal texture component, which results in increasing $\sigma_0$. It is reasonably expected that the stronger basal texture will result in higher $\sigma_0$ and $K$ in the Hall-Petch equation, namely strong grain size dependency of the yield stress.

4. Conclusions

In summary, the following conclusions are reached:

(1) The EBW AZ31 samples subjected to annealing, with a nearly random texture but different grain sizes ($d$), exhibited a clear grain size dependencies of yield stress: $\sigma_{02} = 62 + 202d^{-1/2}$.

(2) The Schmid factor for the basal slip in randomly textured Mg alloys was theoretically deduced to be $\approx 0.031$. The theoretically calculated $\sigma_0$ value of $\approx 65$ MPa is reasonably consistent with the experimental value of $\approx 62$ MPa.

Acknowledgements

The project was sponsored by National Science Council of Taiwan, ROC (94-2216-E-110-010). The author Y. N. Wang is grateful for the partial sponsorship from Natural Science Foundation of China (50471069).

REFERENCES