THE FORMABILITY OF A SHEET OF Mg-9Li-1Y ALLOY AT ROOM TEMPERATURE

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Abstract
The formability of an experimentally produced Mg-9\%Li-1\%Y alloy sheet with a thickness of 0.6 mm is investigated. Uniaxial tension tests and some fundamental press forming tests, such as stretching, deep drawing and bore expanding, are carried out at room temperature. The sheet has sufficiently high ductility. However, ductility decreases with the increase in strain rate. Even at room temperature, the stress is also sensitive to the strain rate. The stress and the work-hardening rate increase with the strain rate. The strain rate sensitivity has influence on the formability in press forming. The critical punch stroke in the stretching test decreases with the increase in punch speed. However, the limiting drawing ratio increases with the punch speed due to the increase in work-hardening rate. The Erichsen value is estimated to be 9 mm, and the limiting drawing ratio amounts to 2.15. It may be concluded that the sheet has sufficiently high formability.

1. INTRODUCTION
Magnesium is one of the lightest materials and has high rigidity. However, the formed products of magnesium have been limited, because magnesium is a hexagonal close-packed metal and has poor formability. It is well known that the addition of lithium to magnesium gives rise to highly workable, body-centred cubic alloys [1-3]. Magnesium-lithium (Mg-Li) alloys exhibit two phase structures between 5 and 11 mass\% Li contents consisting of the $\alpha$ (hcp) magnesium rich and $\beta$ (bcc) lithium rich phases at room temperature. The $\beta$ single phase structure exists for greater than 11 mass\% Li contents. Due to their ultra-low density Mg-Li alloys are attractive, and investigations on alloy design and metallographical as well as mechanical properties of Mg-Li alloys have long been carried out [1-17]. However, few studies have examined the formability of Mg-Li thin sheets from a practical point of view [18, 19].

In this study, the formability of an experimentally produced Mg-9Li-1Y alloy sheet at room temperature is examined. Tensile properties are examined by uniaxial tension tests for various strain rates. Further, some fundamental press-forming tests, such as stretching, deep drawing and bore expanding, are carried out, and the effect of the strain rate sensitivity on the formability is discussed.

2. EXPERIMENTAL
2.1 Material
The material used in this study is a Mg-9mass\%Li-1mass\%Y alloy. The alloy was cast in a high-vacuum induction furnace under an argon atmosphere, and cold rolled iteratively to a thickness of 0.6 mm. The total reduction ratio was about 97 \%. And then, the sheet was annealed at 673 K for 45 min.

Figure 1 shows the X-ray diffraction pattern of the sheet. Strong peaks of Li bcc $\beta$ (200) and (211) planes and other peaks of Li and Mg hcp $\alpha$ planes are observed. The X-ray diffraction pattern shows that the sheet is composed of ($\alpha + \beta$) two phases, mainly of the $\beta$ phase.
Figure 2 shows the microstructure of the sheet. Comparatively large grains of the β phase and fine grains of α phase are distributed stratiform and parallel to the rolling direction. The grain diameters of the α and β phases are measured to be 6 and 13 µm, respectively. The grain size of the present sheet, consisting of Y as a third metal, is very small compared with that of the Mg-8.5Li-1Zn alloy sheet examined in our previous works [18, 19].

2.2 Forming tests
Uniaxial tension tests were carried out in the directions of 0, 45 and 90° to the rolling direction. The gauge length and width of the tensile specimens were 50 and 12.5 mm, respectively. The specimens were elongated by a constant cross-head velocity of between 0.05 and 300 mm min⁻¹. The initial strain rates of the tension tests ranged between 1.4×10⁻⁵ and 8.3×10⁻² s⁻¹.

The stretching tests (the Erichsen tests) were carried out using a hemispherical punch with a diameter of 20 mm. Square specimens with a side length of 90 mm were prepared, and the critical punch stroke at fracture initiation was measured. The tests were carried out for three various punch speeds of 2.5, 10 and 100 mm min⁻¹.

Cylindrical deep drawing tests were carried out using four different flat-headed punches and a hemispherical-headed punch with a diameter, d_p, of 40 mm. The profile radii of the punches, r_p, were 2, 4, 8, 12 and 20 (hemispherical) mm. The diameter and the profile radius of the die were 42 and 6 mm, respectively. Circular blanks of various diameters, d_0, were prepared at intervals of 1 mm. The blank-holder force for each blank was given according to Siebel's equation [20]. The tests were carried out for two kinds of punch speeds, 10 and 100 mm min⁻¹. The limiting drawing ratio, LDR, was evaluated as LDR = d_0/max/d_p, where d_0/max was the maximum diameter of drawable specimens.

The bore expanding tests were carried out using the same tools as for the above deep drawing tests. In addition to the flat-headed punches the conical-headed punch with an angle of 60° was adopted. Circular blanks with a hole machined at the centre were prepared. The diameters of the blank and the bore were 80 and 10 mm, respectively. The blank-holder force and the punch speed were kept constant at 20 kN and 5 mm min⁻¹, respectively, during the test. The bore-expanding ratio, λ, was evaluated as λ = (D_f - D_0)/D_0, where D_f is the critical diameter of the expanded bore at fracture initiation and D_0 the initial bore diameter (= 10 mm).
In the stretching, deep drawing and bore expanding tests a chloric lubricant was used. The coefficient of friction was measured to be 0.12 by the Bowden-Leben friction test.

3. RESULTS AND DISCUSSION

3.1 Tensile properties

Figure 3 shows the true stress-strain ($\sigma$-$\varepsilon$) curves of the sheet in the directions of 0, 45, and 90° to the rolling direction, obtained from the uniaxial tension tests under the condition that the initial strain rate is $8.3 \times 10^{-4}$ s$^{-1}$. The tests were carried out on three samples for each direction. The average values of the tensile properties for each direction for an initial strain rate of $8.3 \times 10^{-4}$ s$^{-1}$ are indicated in Table 1.

Though the elongation in the 90° direction is smaller than that in the 0° direction, the true stress-strain curves for both the directions are almost identical, and the normal anisotropy parameters, $r$, for both the directions are much smaller than 1. On the other hand, the properties in the 45° direction are different from those in the 0 and 90° directions. In the 45° direction, the stress is smaller, the large elongation over 70% is attained, and the $r$-value is high (1.93). These may be due to the following: At the tension test in the 45° direction, the stratiform phases shown in Fig. 2 are in 45° direction to the tensile direction, and therefore, the slipping between the phases may be easy to occur.

$\Delta r$, which indicates the planar anisotropy, is taken as $\Delta r = (r_0 + r_{90} - 2r_{45})/2$, and estimated to have a large negative value of $-1.50$.

Table 1 Tensile properties obtained from uniaxial tension tests at an initial strain rate of $8.3 \times 10^{-4}$ s$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>0°</th>
<th>45°</th>
<th>90°</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proof stress /MPa</td>
<td>137</td>
<td>125</td>
<td>140</td>
<td>131</td>
</tr>
<tr>
<td>Tensile strength /MPa</td>
<td>147</td>
<td>128</td>
<td>146</td>
<td>137</td>
</tr>
<tr>
<td>Elongation /%</td>
<td>34.9</td>
<td>74.0</td>
<td>22.3</td>
<td>51.3</td>
</tr>
<tr>
<td>Normal anisotropy parameter, $r$</td>
<td>0.46</td>
<td>1.93</td>
<td>0.40</td>
<td>1.18</td>
</tr>
</tbody>
</table>
Figure 4 shows the true stress-strain relationships for various initial strain rates, obtained from the uniaxial tension tests in the rolling direction. At comparatively low strain rates the elongation is large. At the lowest strain rate the yielding phenomenon and the work-softening are observed. This yielding phenomenon is similar to that of considerably solution-hardened alloys, such as Al-Mg alloys, at elevated temperatures [21]. A more remarkable feature of the sheet is that not only the elongation, but also the stress depends on the strain rate even at room temperature. The stress and the work-hardening rate increase notably with the strain rate, while the elongation decreases.

Figure 5 shows the relationship between the stress and the strain rate, $\dot{\varepsilon}$, at the strain of 0.1 in log-log scale. Though it varies depending on the range of strain rate, the strain rate sensitivity exponent, $m (\sigma = K_1 \dot{\varepsilon}^m)$, is evaluated to be 0.08 on the average. This value is very high for room temperature. It is interesting that the sheet has the strain rate sensitivity even at room temperature as if at elevated temperatures. This may be due to the low melting point of lithium (454 K).

Figure 6 shows the relationship between the work-hardening exponent, $n$, and the strain rate, when the simple equation of $\sigma = K_2 \varepsilon^n$ is applied for the true stress-strain relationship. At low strain rates the $n$-value is negative, namely the work-softening occurs as shown in Fig. 4. However, the $n$-value increases with the strain rate and shows the high rate of work-hardening at high strain rates.

3.2 Press formability

Figure 7 shows the relationship between the critical punch stroke and the punch speed in stretching test. As can be expected from the relationship between the strain rate and the ductility in tension test, the critical stroke decreases with increase in the punch speed. For the higher forming limit in stretching the working speed should be low. The so-called Erichsen test is usually carried out under a low punch speed of about 5 mm min$^{-1}$. Therefore, the Erichsen value may be estimated to be 9 mm.

Figure 8 shows the relationships between the limiting drawing ratio, LDR, and the punch profile radius, $r_p$, for two kinds of punch speeds, $v_p$, of 10 and 100 mm min$^{-1}$. It is notable that the LDR for the higher speed of 100 mm min$^{-1}$ is larger than that for 10 mm min$^{-1}$ in contrast with the forming limit in the stretching test. In this figure the results in case where the blank-holder force is 10 times higher are indicated, and they also show that the forming limit in deep drawing is higher for the higher punch speed. In deep drawing the forming limit usually depends on the localized necking around the punch corner. As shown in the results of the
tension tests the work-hardening rate is low at low strain rates. Therefore, at lower working speed, the deformation is easy to be localized around the punch corner after the thinning occurred there. On the contrary, at higher working speed, the part of the sheet around the punch corner is work-hardened and the higher LDR is obtained. The LDR amounts to 2.15 for an \( r_p \) of 8 mm.

During deep drawing the so-called ears are formed owing to the planar anisotropy, which makes the yield worse. Figure 9 shows a sample of drawn cup after the deep drawing test. As can be expected from the large negative value for \( \Delta r \), quite large ears are formed in the 45° direction to rolling. The earing ratio, \( h_e \), is given as \( h_e = \frac{2(h_{\text{max}} - h_{\text{min}})}{(h_{\text{max}} + h_{\text{min}})} \), where \( h_{\text{max}} \) and \( h_{\text{min}} \) are average values of four maximum and four minimum heights of drawn cup,
respectively. The relationships between the earing ratio and the drawing ratio for various punch profile radii are indicated in Figure 10. The earing ratio increases linearly with the drawing ratio and is evaluated to be 15 to 20\%, which brings a large loss of crop.

Finally, the results of the bore expanding tests are indicated in Table 2. The bore-expanding ratio, $\lambda$, amounts to 45\% for the flat-headed punch and 80\% for the conical-headed punch.

4. CONCLUSIONS

In this study, the formability of an experimentally produced Mg-9Li-1Y alloy thin sheet was investigated. Uniaxial tension tests for various strain rates between $1.4 \times 10^{-5}$ and $8.3 \times 10^{-2}$ s$^{-1}$ and some fundamental press forming tests were carried out at room temperature. The results are summarized as follows:

(1) The sheet exhibits the sufficiently high ductility at comparatively low strain rates, the average elongation being above 50\% at $8.3 \times 10^{-4}$ s$^{-1}$. The sheet has the strain rate sensitivity even at room temperature. The stress and the work-hardening rate increase notably with the strain rate, while the elongation decreases.

(2) The forming limit in stretching depends mainly on the ductility of the sheet. Therefore, the working speed should be low for the high stretchability. However, the limiting drawing ratio increases with the punch speed due to the increase in work-hardening rate.

(3) The Erichsen value, the limiting drawing ratio and the bore-expanding ratio amount to 9 mm, 2.15 and 80\%, respectively. It may be concluded that the sheet has sufficiently high formability.

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