Elastic and Damping Properties of AZ31 Magnesium Alloy Sheet Processed by High-Temperature Rolling

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Elastic and damping properties of AZ31 magnesium alloy sheet processed by high-temperature rolling were investigated. The specimen rolled at high temperature (798 K) exhibited the significant low basal texture intensity and the wide spread of the basal pole toward the RD and TD, compared with the specimen rolled at 573 K. Young’s modulus of the specimen rolled at 798 K had smaller value at all angles than that of the specimen rolled at 573 K. Besides, the specimen rolled at 798 K exhibited slightly higher internal friction compared with the specimen rolled at 573 K over the strain amplitude range investigated. The suppression of the strong basal texture formation in the specimen rolled at 798 K likely contributed to a reduction of Young’s modulus and an increase in internal friction, because the breakaway stress, which is closely related to the macro-yield stress, decreases with an increase in the Schmid’s factor of basal slip.

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1. Introduction

Magnesium alloys are promising light structural materials because of their excellent properties such as high specific strength and high specific stiffness. For their wider applicability, magnesium alloy sheets with high room temperature formability should be developed. However, (0002) basal planes are aligned parallel to the rolling direction (RD), and the intense basal plane texture is formed during rolling, resulting in the poor formability of rolled magnesium alloy sheets at room temperature.

Recently, magnesium alloy sheets showing excellent room temperature formability have been developed.¹⁻¹² One method for enhancement of room temperature formability of magnesium alloy sheets is the use of improved rolling technologies such as shear rolling¹⁻⁷ and high-temperature rolling.³⁻⁶,⁹⁻¹² High-temperature rolling is suggested to be one of the attractive rolling technologies, because a conventional rolling machine is directly available, if rolling temperature can be set to more than 723 K. The magnesium alloy sheet processed by high-temperature rolling exhibits a significant weak basal texture, resulting in the excellent room temperature formability comparable to those of aluminum alloy sheets.

It is well known that pure magnesium and magnesium alloys have high damping properties compared with various metallic materials.¹³⁻¹⁹ However, damping property of commercial magnesium alloys such as Mg-Al-Zn alloys is not so high compared with that of pure magnesium,¹⁵,¹⁷ thus, application of magnesium alloy sheets for damping materials is still limited.²⁰ In general, elastic and damping properties of metals are recognized to be dependent on microstructural factors such as grain size, precipitates, texture and so on. Among the limited literatures, Sugimoto et al.¹³ investigated the effects of crystal orientation on the elastic and damping properties of pure magnesium, and suggested that elastic and damping properties strongly depend on the crystal orientation according to the Schmid’s law. These reports imply that magnesium alloy sheets with significant weak basal texture may exhibit different elastic and damping properties with those of the conventional magnesium alloy sheets with strong basal texture. However, studies on elastic and damping properties of rolled magnesium alloy sheets with different texture are very few. Especially, there is no study reporting the effects of texture distribution on the elastic and damping properties of rolled magnesium alloy sheets. Thus, in the present paper, AZ31 (Mg-2.7Zn-0.8Al-0.4Mn in mass%) alloy sheets were processed by high-temperature rolling, and the elastic and damping properties of the sheets were investigated.

2. Experimental Procedure

A specimen with 120 mm length, 80 mm width and 5 mm thickness was machined from an as-received extrusion of AZ31 (Mg-2.7Al-0.8Zn-0.4Mn in mass%) alloy, and then was homogenized at 723 K for 20 h prior to rolling. The specimen was rolled from 5 to 1.26 mm in thickness by 6 passes at 723 K, and was subsequently rolled down to 1.0 mm by a single pass at 798 K, which is close to the solidus temperature (839 K) of the AZ31 alloy.²¹ The reduction per pass was 20% for each pass and the total reduction was 80%. As a reference, the specimen rolled at low temperature was prepared, where the specimen was rolled from 5 to 1.0 mm by 7 passes at 573 K at a rolling reduction of 20%. Finally, the rolled specimens were fully annealed at 623 K for 5.4 × 10³ s in order to minimize dislocation density in the rolled specimens. Hereafter, the specimen rolled at 798 K at final rolling pass is called the specimen rolled at 798 K, and the specimen rolled at 573 K through the rolling schedule is called the specimen rolled at 573 K.

The specimen for the measurement of elastic and damping properties with a 52 mm length, 10 mm width and 1 mm thickness was machined from the rolled specimen. Young’s
modulus \((E)\) was measured by the free resonance transverse vibration method, and the internal friction \((Q^{-1})\) of the rolled specimens was measured by the resonance transverse vibration method by using cantilevered beam specimen, where the angles between the longitudinal direction of the specimen and the RD were set to 0°, 45° and 90° for the measurement of Young’s modulus and 0° and 90° for the measurement of internal friction.

Tensile specimens with a 12 mm gage length, a 4 mm gage width and a 1 mm gage thickness were machined from the rolled specimens. Tensile tests were carried out with an initial strain rate of \(3 \times 10^{-3} \text{ s}^{-1}\), where the angles between the tensile direction and the RD were set to 0°, 45° and 90°. The microstructures of the rolled specimens were investigated by optical microscopy, and the (0002) plane pole figure of the rolled specimens at the center through a thickness was investigated by Schulz reflection method.

3. Results and Discussion

The microstructures of the specimens rolled at 798 and 573 K in the RD-ND plane are shown in Fig. 1, where the ND is the normal direction. The average grain sizes were 15.4 μm for the specimen rolled at 798 K and 14.7 μm for the specimen rolled at 573 K. There was a little difference in grain size between them.

The (0002) plane pole figures of the specimens rolled at 798 and 573 K are summarized in Fig. 2. Note that the basal texture intensity of the specimen rolled at 798 K was significantly lower than that of the specimen rolled at 573 K. The (0002) plane of the specimen rolled at 573 K intensively distributed parallel to the sheet plane in which there was a tendency to align the basal poles with the ND, and there was a slight spreading of the basal poles toward the RD. The similar tendency was observed in the specimen rolled at 798 K, although there were large differences, namely, there was a symmetrical splitting of the peaks in intensity by ±20° from the ND toward the RD, and also there was a wider spread of the basal pole toward the transverse direction (TD). The significant reduction of basal texture intensity and the wide spread of the basal pole toward the RD and TD in the specimen rolled at 798 K are likely ascribed to the occurrence of discontinuous static recrystallization during annealing.\(^6\,12\)

Tensile properties including ultimate tensile strength (UTS), 0.2% proof stress (YS), fracture elongation (FE), uniform elongation (UE), \(\nu\)-value and strain hardening...
The YS and r-value increased with increasing the angle between the RD and the tensile direction, while the n-value showed a converse behavior. This is due to the spread of the (0002) orientation and the inclination of basal poles in the RD, which are favored for basal slip during deformation in the tensile direction. It is noted that the specimen rolled at 798 K exhibited the lower YS and r-value and higher FE, UE and n-value than the specimen rolled at 573 K, suggesting that the suppression of the strong basal texture formation was attributed to the low yield stress and enhanced ductility of the specimen rolled at 798 K.

Table 1 Tensile properties at room temperature of the rolled and subsequently annealed AZ31 alloy sheets (UTS, ultimate tensile strength; YS, 0.2% proof stress; FE, fracture elongation; UE, uniform elongation; r-value, Lankford value; n-value, strain hardening exponent.)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Orientation</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>FE (%)</th>
<th>UE (%)</th>
<th>r-value</th>
<th>n-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled at 798 K</td>
<td>0°</td>
<td>258</td>
<td>143</td>
<td>29</td>
<td>22</td>
<td>1.1</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>260</td>
<td>149</td>
<td>28</td>
<td>21</td>
<td>1.2</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>262</td>
<td>153</td>
<td>28</td>
<td>20</td>
<td>1.3</td>
<td>0.25</td>
</tr>
<tr>
<td>Rolled at 573 K</td>
<td>0°</td>
<td>268</td>
<td>178</td>
<td>24</td>
<td>17</td>
<td>2.8</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>269</td>
<td>182</td>
<td>24</td>
<td>16</td>
<td>3.0</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>271</td>
<td>191</td>
<td>23</td>
<td>15</td>
<td>3.6</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Fig. 3 Young’s modulus in the longitudinal direction of the specimen machined from rolled and subsequently annealed AZ31 alloy sheets, where the orientation indicates the angle between the longitudinal direction of the specimen and the RD.

Fig. 4 Variation in internal friction as a function of strain amplitude in rolled and subsequently annealed AZ31 alloy sheets: (a) specimen rolled at 798 K and (b) specimen rolled at 573 K. The orientation indicates the angle between the longitudinal direction of the specimen and the RD.

The YS and r-value of the rolled specimens are summarized in Table 1. The YS and r-value increased with increasing the angle between the RD and the tensile direction, while the n-value showed a converse behavior. This is due to the spread of the (0002) orientation and the inclination of basal poles in the RD, which are favored for basal slip during deformation in the tensile direction. It is noted that the specimen rolled at 798 K exhibited the lower YS and r-value and higher FE, UE and n-value than the specimen rolled at 573 K, suggesting that the suppression of the strong basal texture formation was attributed to the low yield stress and enhanced ductility of the specimen rolled at 798 K.

Figure 3 shows the Young’s modulus of the rolled specimens rolled at 798 and 573 K with different angles between the longitudinal direction of the specimen and the RD. In both the specimens, the Young’s modulus increased with an increase in angles, implying that the spread of basal pole toward the RD promoted a decrease in Young’s modulus. It is noted that the Young’s modulus of the specimen rolled at 798 K had smaller value at all angles than that of the specimen rolled at 573 K. This result indicates that the elastic properties of the rolled specimen strongly depend on the basal pole distribution.

Figure 4 shows the variation in internal friction of the specimens rolled at 798 and 573 K as a function of strain amplitude (ε). The range of strain amplitude was set from 0.5 × 10^-4 to 1.1 × 10^-3. The internal friction of both the specimens exhibited strain-amplitude dependent with the same manner as the previous studies, suggesting that the main damping mechanism is the dislocation damping, which is caused by the interaction between the dislocation and impurity atoms. In Fig. 4, the internal friction at the strain amplitude of 5 × 10^-4 for the specimen rolled at 798 K was 1.69 × 10^-3 at 0° and 1.68 × 10^-3 at 90°, and that for the specimen rolled at 573 K was 1.63 × 10^-3 at 0° and 1.57 × 10^-3 at 90°. Thus, the results in Fig. 4 indicate that the specimen rolled at 798 K demonstrated slightly higher internal friction compared with the specimen rolled at 573 K over the strain amplitude range investigated. It is suggested that the internal friction has close relationships...
with the basal pole distribution similar to the case of Young’s modulus.

It is known that the breakaway stress, which is defined as the stress where the basal dislocations bow out to move against the binding force of impurity, is closely related to the macro-yield stress, and it decreases with an increase in the Schmid’s factor. Sugimoto et al. investigated the effects of crystal orientation on elastic and damping properties of mono and polycrystalline pure magnesium, and suggested that the Young’s modulus and internal friction have the minimum and maximum values, when the Schmid’s factor for basal slip has the maximum value of around 0.5, respectively. It is interesting to note that an elastic constant of shear elasticity (C_{44}) has a much lower value than that of orthogonal elasticity (C_{11} and C_{33}) in the case of magnesium crystal. Provided that the macroscopic elastic constants are determined by basal texture distribution, the suppression of basal texture formation may result in the decrease in the elastic constants of the rolled specimen. In the present study, the specimen rolled at 798 K exhibited significant reduction of basal texture intensity and the wide spread of the basal pole toward the RD and TD. This fact implies that the Schmid’s factor for basal slip had a large value for the majority of grains in the specimen rolled at 798 K. This may be one of the main reasons for the lower Young’s modulus and higher internal friction on the specimen rolled at 798 K. Thus, it is suggested that a suppression of the strong basal texture formation by high-temperature rolling is effective for controlling elastic and damping properties of the rolled magnesium alloy sheets, at least in the strain amplitude range investigated.

According to the “Granato-Lücke” theory, a plot of the ln(Q H^-1 · ε) and the inverse of strain amplitude (1/ε) gives a linear relationship, if the main damping mechanism is the dislocation damping, where Q H^-1 is the amplitude-dependent internal friction. Figure 5 shows the “G-L plots” of the specimens rolled at 798 and 573 K. The Q^{-1} is used as Q H^-1 since Q H^-1 is almost equal to Q^{-1} at comparatively high strain amplitude. In general, the damping properties of magnesium are weakly related to the strain amplitude at the low strain amplitude, while it is strongly related to the strain amplitude at high strain amplitude. The linear relationship in Fig. 5 can be roughly divided into two parts at around 5 × 10^{-4} of strain amplitude (2000 of 1/ε), indicating that the effects of strain amplitude on the internal friction in the present study are qualitatively the same as the previous studies. Nisiyama et al. suggested that the deviation from the straight line in the G-L plot is ascribed to the generation of deformation twins. Kageyama et al. pointed out that the deviation from the straight line in the G-L plot is likely because the effects of extended dislocation and thermal activation process are not taken into consideration in Granato-Lücke theory. Identification of twinning and generation of extended dislocation in the specimens rolled at 798 and 573 K is still in progress. Further research is underway to understand the role of damping mechanisms of the magnesium alloy sheets rolled at high temperature.

4. Summary

Elastic and damping properties of AZ31 magnesium alloy sheet processed by high-temperature rolling were investigated. The following results were obtained:

(1) The specimen rolled at high temperature (798 K) exhibited the significant reduction of basal texture intensity and the wide spread of the basal pole toward the RD and TD compared with the specimen rolled at 573 K. As a result of tensile test, the specimen rolled at 798 K exhibited the lower 0.2% proof stress and r-value and higher elongation and n-value than the specimen rolled at 573 K, suggesting that the suppression of the strong basal texture formation was attributed to the low yield stress and enhanced ductility of the specimen rolled at 798 K.

(2) Young’s modulus of the specimen rolled at 798 K had smaller value at all angles than that of the specimen rolled at 573 K. Besides, the specimen rolled at 798 K demonstrated slightly higher internal friction compared with the specimen rolled at 573 K over the strain amplitude range investigated. The lower Young’s modulus and higher internal friction in the specimen rolled at 798 K are likely ascribed to the suppression of the basal texture formation, because the breakaway stress, which is closely related to the macro-yield stress, decreases with an increase in the Schmid’s factor of basal slip.

Fig. 5 G-L plots for the rolled and subsequently annealed AZ31 alloy sheets: (a) specimen rolled at 798 K and (b) specimen rolled at 573 K. The orientation indicates the angle between the longitudinal direction of the specimen and the RD.
REFERENCES