Springback Characteristics of Magnesium Alloy Sheet AZ31B in Draw-Bending

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In this study, we carried out a two-dimensional draw-bending test on an AZ31B magnesium alloy sheet at various forming temperatures and blank holding forces, and the springback characteristics of the Mg alloy sheet were systematically examined. The amount of springback decreased with increasing temperature and blank holding force. The decrease in the amount of springback caused by the increase in temperature was much larger than that caused by the increase in blank holding force, which indicated that increasing temperature was much more effective for decreasing the amount of springback than increasing blank holding force. The amount of springback became negligible at 200°C and above. This result was attributable to the following factors: (a) flow stress decreased rapidly as temperature increased, (b) reverse bending on the sidewall arose at 150°C and above, and (c) fine grains due to dynamic recrystallization were formed at 200°C and above. Microstructure evolution during the draw-bending test was also observed with particular focus on twinning, and its effects on springback characteristics were studied in detail. [doi:10.2320/matertrans.P-M2010803]

(Received August 31, 2009; Accepted January 18, 2010; Published March 25, 2010)

Keywords: magnesium alloy sheet AZ31B, springback, sheet metal forming, warm forming, reverse bending, twinning, recrystallization

1. Introduction

Magnesium (hereafter Mg) alloys are the lightest materials used for structural components owing to their high specific strength and stiffness.1,2,11 Besides, Mg alloys also have advantages in terms of functional properties, such as recyclability1,3 and high electromagnetic shielding.1,4-6 Because of increasing demand for lightweight materials for automobile and electrical devices,1,2 Mg alloys have recently been attracting much attention. Mg alloys are now applied in various components, such as the housing of laptop computers and cellular phones, and automobile body structures.

Conventionally, the above components using Mg alloys are mainly manufactured by die casting and thixoforming.1,4-6 The press forming of Mg alloy sheets has recently attracted attention because the application of press forming can further expand the use of Mg alloys. However, there are very few applications of press forming because Mg alloy sheets have poor formability at room temperature (RT) mainly owing to the limited number of slip systems in hexagonal close-packed (hereafter HCP) Mg alloys. Because the critical shear stress of non basal slip systems markedly decreases with an increase in forming temperature, warm forming is one of the effective methods of improving formability. Recently, warm forming has received much interest and many studies have been carried out particularly on warm deep-drawing processes.5-10

Springback is one of the most critical defects in sheet metal forming, and a considerable amount of time is needed to compensate for this defect. For conventional structural sheet metals such as steel and aluminum, springback characteristics have been extensively studied both experimentally and numerically (e.g., Refs. 11–14). On the other hand, research studies on the springback of Mg alloy sheets are few. Chen and Huang,15 Paisarn et al.,16 and Bruni et al.17 carried out experiments on air bending processes of Mg alloy sheets and investigated the effects of temperature on springback. Kim et al.4 and Matsui et al.18 conducted experiments on two-dimensional draw-bending processes and studied the effects of temperature on springback. They reported that the amount of springback decreases with increasing temperature and vanishes at about 300°C. They explained that this is attributable to the decrease in flow stress with increasing temperature. Although the decrease in flow stress is apparently an important factor, this alone cannot explain why springback vanishes at 300°C. Furthermore, Young’s modulus, one of the important factors determining the amount of springback, may also change with temperature. Kim et al. have examined the effect of blank holding force (BHF) on springback.4,11 However, considerable research is still required to understand the effect of BHF in detail. In draw-bending, reverse bending may sometimes arise on the sidewall depending on the forming conditions, reducing the amount of springback.14,19 Indeed, even springforward may arise when reverse bending takes place. Therefore, it is crucial to examine the occurrence of reverse bending during draw-bending, which has not been studied until now.

It is also necessary to determine the effect of microstructure evolution during deformation on springback because both twinning and recrystallization affect the deformation of Mg alloy sheets. Twinning plays a significant role in the inflection of the stress-strain curve when Mg alloy sheets are subjected to in-plane compression at RT.20 This is because a strong basal texture with most of the c-axes aligned in the sheet normal direction is initially formed in rolled Mg alloy sheets.21,22 Recently, it has been reported that in-plane tension after compressive deformation at RT is initially dominated by the disappearance of twins, yielding an inflected stress-strain curve similar to that observed in in-plane compression.21 Similar deformation characteristics have also been observed in extruded Mg alloys.23,24 In typical draw-bending, a sheet undergoes bending at the die shoulder, followed by unbending on the sidewall; thus,
sheet surfaces undergo tension and compression during the process. Therefore, similar microstructure evolution should take place on the surfaces of sheet. However, no such microstructure observations during draw-bending tests have been reported yet.

In this study, we carried out a two-dimensional draw-bending test on an AZ31B Mg alloy sheet at various temperatures and BHF. Both macroscopic investigations, including the measurement of sidewall opening and the observations of reverse bending at a sidewall, and microscopic investigations of microstructure evolution were conducted, and the springback characteristics of the Mg alloy sheet were systematically studied in detail.

2. Tensile Properties of Material

2.1 Experimental procedures

A commercial Mg alloy sheet of AZ31B with a 0.8 mm thickness produced by Osaka Fuji Corporation was used. The material was annealed at 350°C for 1.5 h to obtain an O temper before the experiment. A uniaxial tensile test was carried out at various temperatures to determine the tensile properties of the Mg alloy sheet. JIS13B tensile specimens were machined parallel to the rolling direction. The experiment was carried out at 25 (RT), 75, 100, 150, 200, and 225°C. The experiment at elevated temperatures was carried out in a furnace, in which the internal atmosphere was heated with a heater and controlled to within ±5°C of the preset temperature during the experiment. A strain gauge (Kyowa Electronic Instruments Co., KFH-5-120-C1-23) was used to precisely measure the small initial strains and Young’s modulus. On the other hand, the total strain to fracture at elevated temperatures was measured by image analysis using a video camcorder placed outside the furnace, whereas that at RT was measured using an extensometer. In both cases, the gage length was 50 mm. Each tensile test was carried out at an initial strain rate of 0.003 s⁻¹.

2.2 Tensile properties

The nominal stress-nominal strain curves obtained are shown in Fig. 1. The fracture strain is about 20% at RT and increases with temperature. At 200°C and above, the fracture strain is about 60%, consistent with results in the literature. On the other hand, the total strain to fracture at elevated temperatures was measured by image analysis using a video camcorder placed outside the furnace, whereas that at RT was measured using an extensometer. In both cases, the gage length was 50 mm. Each tensile test was carried out at an initial strain rate of 0.003 s⁻¹.

Figure 2 illustrates the relationships of temperature with tensile strength and 0.2% proof stress. Both tensile strength and 0.2% proof stress decrease almost linearly with increasing temperature. The tensile strength at 225°C is almost half as large as that at RT. Figure 3 shows the relationship between temperature and Young’s modulus. Young’s modulus is almost constant from RT to 100°C, but it decreases when the temperature exceeds 100°C. Young’s moduli at RT and 225°C are about 42 and 27 GPa, respectively. These results are qualitatively in agreement with those in the literature.

Generally, decreases in tensile strength and 0.2% proof stress, i.e., flow stress, yield a smaller amount of springback, whereas a decrease in Young’s modulus yields a larger amount of springback. Therefore, from the viewpoint of tensile properties, the change in the amount of springback with increasing temperature is determined from the relationship between flow stress and Young’s modulus.

Figure 4 shows the nominal stress-nominal strain curves at RT, 150°C, and 200°C in which the specimen was unloaded and reloaded during the test. The result for a mild steel sheet is also shown in Fig. 4(a) for reference.
Compared with the mild steel sheet, the Mg alloy sheet exhibits significant strain hysteresis during unloading and reloading. This has also been reported in the literature. Cáceres et al. have shown that the hysteresis loops progressively developed up to a plastic strain of about 1–2%. As shown in Figs. 4(b) and 4(c), strain hysteresis is observed irrespective of temperature. Because strain hysteresis clearly yields a large amount of springback, these results show that its effect on springback characteristics should be studied at various temperatures. This will be part of our future work.

2.3 Microstructures

Microstructures before and after the tensile test are shown in Fig. 5. Sheet surfaces near fracture regions were observed for specimens after the test. The initial average grain diameter is about 20 μm. The grains are equiaxial, and twins are rarely observed before the test (Fig. 5(a)). At RT, the grain size remains the same and a small number of twins are observed (Fig. 5(b)). At 150°C, most grains elongate along the tensile direction and fine grains start to form near the grain boundaries (Fig. 5(c)). These fine grains may be attributed to dynamic recrystallization. They are dominant over the entire area of the specimen when the temperature is 200°C and above (Fig. 5(d)). This result indicates that the recrystallization as well as the activation of nonbasal slip systems is one of the factors causing the changes in the tensile properties at elevated temperatures shown in Figs. 2 and 3.

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3. Two-Dimensional Draw-Bending Test

3.1 Experimental procedures

Figure 6 shows the experimental setup developed for the two-dimensional draw-bending test. The die and punch shoulder radii, \( r_d \) and \( r_p \), respectively, were 5 mm, and the clearance between the punch and the die, \( c \), was 1.6 mm. The dimensions of the sheet blank were 220 mm long, 50 mm wide, and 0.8 mm thick. The longitudinal direction of the sheet was parallel to the rolling direction. Lubrication oil (G-2576, Nihon Kohsakuyu Co.) was used at all temperatures. BHF was supplied by four springs with a spring constant of 235.7 N/mm and was set by screw nuts. BHF of 0, 0.49, 0.98, 1.96, and 4.90 kN were applied. Note that the above BHFs do not include the empty weight of the blank holder, which is about 0.17 kN.

The tools were heated using heaters inserted into the tools, and their temperatures were controlled to preset values using temperature controllers. Temperatures of 25 (RT), 75, 100, 150, 200, and 225°C were used. Insulator plates (Miorek HR-1(PMX-561), Ryoden Kasei Co.) were intercalated between the die and the lower base plate and between the blank holder and the upper base plate to avoid heat transfer from the tools to the base plates. Preliminary experiments showed that the temperature distributions on the sheet could be considered sufficiently uniform with a maximum error of 7.5% from the preset temperatures.

The sheet was drawn with a constant punch speed of 10 mm/min up to a punch stroke of 50 mm. At this punch speed, the sheets were drawn with a constant punch speed of 10 mm/min up to a punch stroke of 50 mm. At this punch speed, the sheets were drawn with a constant punch speed of 10 mm/min up to a punch stroke of 50 mm. At this punch speed, the sheets were drawn with a constant punch speed of 10 mm/min up to a punch stroke of 50 mm. At this punch speed, the sheets were drawn with a constant punch speed of 10 mm/min up to a punch stroke of 50 mm.
Fig. 5 Microstructures before and after the tensile test. The double-headed arrow denotes the tensile direction. (a) Before the test, after the test at (b) RT, (c) 150°C, and (d) 200°C.

Fig. 6 Experimental setup used in the draw-bending test.

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speed, the sheet underwent bending and unbending at the die shoulder at a nominal strain rate of about 0.003 s⁻¹, which is in agreement with that in the above-mentioned uniaxial tensile test. The amount of springback after the draw-bending process was determined by the die shoulder and then comes in contact with the die in the middle of the sidewall, as indicated by the arrows in the figures. Such deformation is the so-called reverse bending. Reverse bending clearly arises at 225°C but is negligible at RT, although a small amount of reverse bending arises at RT with a BHFs of 4.9 kN (Fig. 9(c)). In this experiment, reverse bending clearly arises at 150°C and above, and this trend is independent of BHFs.

### 3.2.2 Deformation profile on the sidewall

Figure 9 shows the deformation profiles on the sidewall at a punch stroke of 50 mm, i.e., before springback, at RT and 225°C and with BHFs of 0 and 4.9 kN.

In the results for 225°C with BHFs of 0 and 4.9 kN (Figs. 9(b) and 9(d), respectively), the sheet tends to come in contact with the punch after passing through the die shoulder and then comes in contact with the die in the middle of the sidewall, as indicated by the arrows in the figures. Such deformation is the so-called reverse bending. Reverse bending clearly arises at 225°C but is negligible at RT, although a small amount of reverse bending arises at RT with a BHFs of 4.9 kN (Fig. 9(c)). In this experiment, reverse bending clearly arises at 150°C and above, and this trend is independent of BHFs.

### 3.2.3 Discussion

As mentioned in Section 2.2, the variation in the sidewall opening with increasing temperature may be determined from the relationship between flow stress and Young’s modulus. Because the sidewall opening decreases as temperature increases (Fig. 8), the decrease in flow stress should have a greater effect on the variation in sidewall opening. To numerically confirm this, a finite element simulation of draw-bending was carried out. A homemade program using a static-implicit method was used. Because the purpose of the simulation was to qualitatively examine the effects of flow stress and Young’s modulus on springback, simple simulation conditions were employed. Owing to the symmetry of the deformation, the plane strain condition was assumed in the width direction and only half of the part of the sheet was modeled. The temperature of the sheet was assumed to be constant during the process. Only the tensile properties (Figs. 1–3) were used as the mechanical properties in the simulation, and the inflected stress-strain curve under compression was not taken into account. The simulation was carried out under two conditions: (a) both the stress-strain curve and Young’s modulus were changed in accordance with their dependence on temperature; and (b) only the stress-strain curve was changed in accordance with its dependence on temperature and Young’s modulus was fixed at 42 GPa (Young’s modulus at RT).

Figure 10 shows the relationship between sidewall opening and temperature obtained by the simulation. Although the change in Young’s modulus with temperature is considered in case (a), the sidewall opening shows the same decreasing tendency with increasing temperature as that in case (b). These results support the notion that the decrease in flow stress has a much greater effect on the variation in sidewall opening than the decrease in Young’s modulus. On the other hand, the decrease in Young’s modulus should also be considered for the quantitative prediction of springback because the change in the sidewall opening caused by the decrease in Young’s modulus is also measurably large (Fig. 10).

The sidewall opening decreases when reverse bending takes place on the sidewall during the draw-bending process. This mechanism is explained by the fact that a sheet is unloaded by reverse bending; therefore, stress on the sidewall decreases. Reverse bending is easier to induce at 150°C and above, as shown in Fig. 9, indicating that the
sidewall opening is decreased not only by a decrease in flow stress but also by reverse bending at elevated temperatures. Because the mechanism of reverse bending is still unclear, the reason why reverse bending is easier to induce at elevated temperatures should be further investigated.

3.3 Microstructures

Owing to bending and unbending during the draw-bending process, the sheet surface on the die side undergoes compression at the die shoulder, followed by tension on the sidewall, whereas these occur in reverse order on the opposite surface. To investigate how microstructures evolve with bending and unbending, microstructures at both the die shoulder and the sidewall were observed. For each position, parts near both sheet surfaces were observed. For convenience, the part near the sheet surface on the die side is hereafter termed the CT (compression-tension) surface, whereas that on the opposite surface is denoted the TC (tension-compression) surface. The results are discussed using the microstructures obtained at RT and 225°C for BHF of 0 kN. Noted that the microstructures near the midsurface of the sheet remained unchanged during the process regardless of temperature. This is because the strain caused by bending and unbending is negligible near the midsurface. Therefore, no results obtained near the midsurface are shown in the present paper.

Figures 11 and 12 show the microstructures on the CT and TC surfaces after the test at RT, respectively. Twins were rarely observed before the draw-bending test, as shown in Fig. 5(a). On the CT surface, many twins with lenticular morphology arise after bending (at the die shoulder, Fig. 11(a)). This is because a strong basal texture with most of the c-axes aligned in the sheet normal direction initially forms in rolled Mg alloy sheets. However, most of the twins vanish after unbending (on the sidewall, Fig. 11(b)). It has recently been reported that in-plane tension after compressive deformation is initially predominated by the disappearance of twins, yielding a similar inflected stress-strain curve to that observed in in-plane compression. Figure 11 shows that the twinning evolution observed in in-plane compression-tension deformation is also observed on the CT surface, suggesting that the deformation near the CT surface is governed by inflected stress-strain curves that are notably different from those shown in Fig. 1.

On the TC surface, twins are rarely observed after bending (at the die shoulder, Fig. 12(a)), whereas a number of twins arise after unbending (on the sidewall, Fig. 12(b)). The trend showing that twins arise under compression is the same as that on the CT surface, but the number of twins observed on the TC surface after unbending appears to be smaller than that observed on the CT surface after bending (Fig. 11(a)). These results suggest that the activation of twins is dependent on the strain path. Since twinning is responsible for the inflection in the stress-strain curve as mentioned above, this result indicates that the stress-strain curve near the TC surface may be different from that near the CT surface. These results show that the effects of twinning on the stress-strain
The curve should be investigated in greater detail to further understand the springback characteristics of Mg alloy sheets at RT.

Figure 13 shows the microstructures on the CT surface after the test at 225 °C. At both the die shoulder and the sidewall, fine grains form near grain boundaries, and twins are rarely observed. As shown in Fig. 14, the trend in microstructure evolution on the TC surface clearly resembles that on the CT surface. The fine grains are probably attributable to dynamic recrystallization because no such grains are observed near the midsurface of the sheet, as mentioned above. The number of fine grains observed after the draw-bending test is much smaller than that observed after the tensile test (Fig. 5) because the magnitude of strain that arises during the draw-bending test is much smaller than that arising during the tensile test. Interestingly, the number of fine grains is larger on the sidewall (Figs. 13(b) and 14(b)) than that at the die shoulder (Figs. 13(a) and 14(a)) because the sheet is subjected to a larger plastic deformation by unbending on the sidewall. Similar tendencies are observed in the tests at 200 °C and above; however, no fine grains are observed at 150 °C and below. Because fine grains are stress-free, the sidewall opening may also be decreased by the formation of fine grains at 200 °C and above.

From the above-mentioned macroscopic and microscopic observations, we can conclude that the sidewall opening becoming negligible at 200 °C and above is due to multiple factors: a decrease in flow stress, the occurrence of reverse bending on the sidewall, and the formation of fine grains due to dynamic recrystallization.

4. Conclusions

In this study, a two-dimensional draw-bending test on an AZ31B Mg alloy sheet was carried out at various forming temperatures and BHFs, and the springback characteristics of the sheet were examined in detail. The following conclusions were drawn.
(1) Flow stress decreases almost linearly with increasing temperature. Young’s modulus is almost constant from RT to 100°C; however, it decreases when the temperature exceeds 100°C. The finite element simulation revealed that a decrease in flow stress has a greater effect on the variation in springback than a decrease in Young’s modulus.

(2) The amount of springback decreases with increases in temperature and BHF. The decrease in the amount of springback caused by the increase in temperature is much larger than that caused by the increase in BHF, which indicates that increasing the temperature is much more effective for reducing the amount of springback than increasing BHF.

(3) The amount of springback becomes negligible at 200°C and above. This result is attributable to multiple factors: (a) flow stress decreases rapidly as temperature increases, (b) reverse bending on the sidewall arises at 150°C and above, and (c) fine grains due to dynamic recrystallization are formed at 200°C and above.

(4) The occurrence and disappearance of twins are clearly observed near sheet surfaces during the draw-bending test at RT, and this microstructure evolution resembles that observed in the cyclic in-plane tension-compression test in the literature. The effects of twinning on the stress-strain curve should be investigated in greater detail to further understand the springback characteristics of Mg alloy sheets at RT.

Acknowledgements

The authors would like to acknowledge Professor Mamoru Mabuchi of Kyoto University, Associate Professor Takashi Iizuka of Kyoto Institute of Technology, and Assistant Professor Ryo Matsumoto of Osaka University for their assistance in the use of the experimental apparatuses. This research was supported by a Grant-in-Aid for Young Scientists (B) (#18760547) provided by the Japan Society for the Promotion of Science, and by Suzuki and Amada Foundation research promotion grants.
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