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Anisotropic deformation behavior during cup drawing at room temperature of a ZX10 magnesium alloy sheet

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Abstract. Magnesium (Mg) alloy sheets have low density and high specific strength; thus, they are expected to facilitate weight reduction of structural components. However, because of the strong crystal anisotropy of the hexagonal structure and the strong basal texture observed in typical rolled Mg alloy sheets, their press formability at room temperature is low. To improve the room-temperature press formability, ZX series Mg alloy sheets that weakened the basal texture have recently been developed. The plastic deformation behavior of a rolled Mg-1.5mass%Zn-0.1mass%Ca (ZX10Mg) alloy sheet was studied in a previous study [7], and it was reported that the plastic deformation behavior showed strong in-plane anisotropy and differed notably from that of AZ series rolled Mg alloy sheets. In the present study, cylindrical cup drawing of a ZX10Mg alloy sheet was performed at room temperature and the drawability was examined in terms of cup height distributions, strain evolution, and texture evolution. The cup height differed significantly between the rolling and transverse directions. The thickness at the cup edge was the largest in the rolling direction and the smallest in the transverse direction. The magnitude relationship of the thickness correlated with the Lankford values under compression. The mechanism that yielded the difference in texture evolution was also discussed.

Introduction

Magnesium (Mg) alloy sheets have low density and high specific strength; thus, they are expected to facilitate weight reduction of structural components [1]. However, because of the strong crystal anisotropy of the hexagonal structure and the strong basal texture observed in typical rolled Mg alloy sheets, their press formability at room temperature is low [2,3]. To improve the press formability, ZX series Mg alloy sheets that weakened the basal texture have recently been developed. Chino et al. [4-6] conducted the room-temperature Erichsen cupping test of ZX series Mg alloy sheets and reported that their stretchability is superior to that of AZ series rolled Mg alloy sheets. Hama et al. [7] reported that the work-hardening behavior of a rolled Mg-1.5mass%Zn-0.1mass%Ca (ZX10Mg) alloy sheet shows strong in-plane anisotropy, which differs notably from those of typical AZ series rolled Mg alloy sheets. Nakata et al. [8] conducted room-temperature V-bending tests of a ZX10 Mg alloy sheet and studied the bendability in terms of activities of slip and twinning systems. It is expected that ZX series Mg alloy sheets exhibit not only better stretchability and bendability but also superior drawability, which is also one of the important properties for industrial applications. It is also presumed from the previous study that anisotropic deformation is exhibited during drawing because of the strong in-plane anisotropy of the work-hardening behavior. However, room-temperature drawability of ZX series Mg alloy sheets have not been studied yet.

In the present study, cylindrical cup drawing of a ZX10Mg alloy sheet was performed at room temperature and the drawability was discussed in terms of cup height and strain distributions.

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Texture evolution was also measured to discuss the correlation between the macroscopic and mesoscopic deformation behaviors.

Experimental Methods

A rolled ZX10 Mg alloy sheet with 1.0 mm thickness produced by Sumitomo Electric Industries, Ltd. [7] was used. Circular cup drawing tests were conducted at room temperature. The experimental procedures were the same as those reported in a literature [9]. A photograph of the experimental setup for cup drawing test is shown in Fig. 1. The diameters of punch and die cavity were 27.8 mm and 30 mm, respectively. The punch and die shoulder radii were 5.0 mm and 7.0 mm, respectively. The diameter of the circular specimen was 40 mm, which corresponds to the drawing ratio of 1.33. The distance between the die and the blank holder was set to 1.1 mm and kept unchanged during forming. A solid lubricant (Moly Paste, Sumico Lubricant Co.) was used for lubrication between the sheet and the dies. The punch was penetrated to a stroke of 16 mm with a punch speed of 5 mm/min.

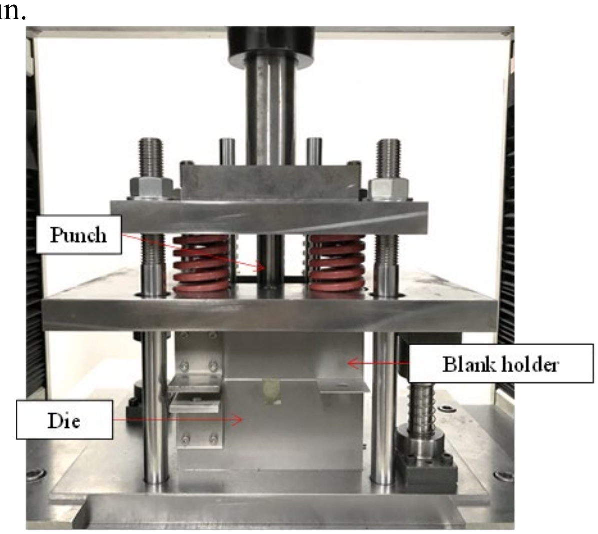

Fig. 1. Experimental setup for the cylindrical cup drawing.

Thickness and cup height of the products were measured using a micrometer and a two-dimensional laser displacement sensor (LJ-V7080, Keyence Co.), respectively. Electron backscattered diffraction (EBSD) measurements were conducted to measure the texture at some points. Fig. 2 shows the pole figure of the initial sample [7]. In the (0001) pole figure, strong peaks appeared in the vicinity of the normal direction (ND), but at the same time weak peaks appeared near the transverse direction (TD), showing that the basal texture is less pronounced than that of typical AZ series rolled Mg alloy sheets [10, 11].

Results and Discussion

Figs. 3 (a) and 3 (b) show the photograph of a drawn cup and the distributions of cup height in the circumferential direction at different punch strokes, respectively. In Fig. 3 (b), the vertical axis denotes the relative height in which the height at the rolling direction (RD) was set to zero in order to exclude the effect of the curvature at the cup bottom. Moreover, considering the symmetry of the deformation, only the results in the first quadrant is shown.

The cup height was larger in the TD than in the RD already at the stroke of 8 mm. The increasing trend is pronounced from the angle of 15° to 60°. The cup height increased with increasing the punch stroke. This trend was more pronounced in the vicinity of the angle of 60°, which eventually

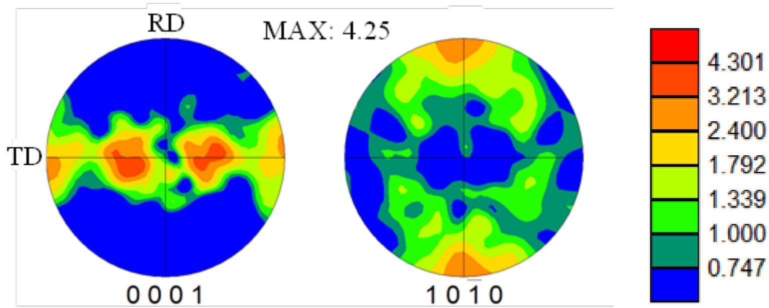

Fig. 2. Initial pole figures of the sample.

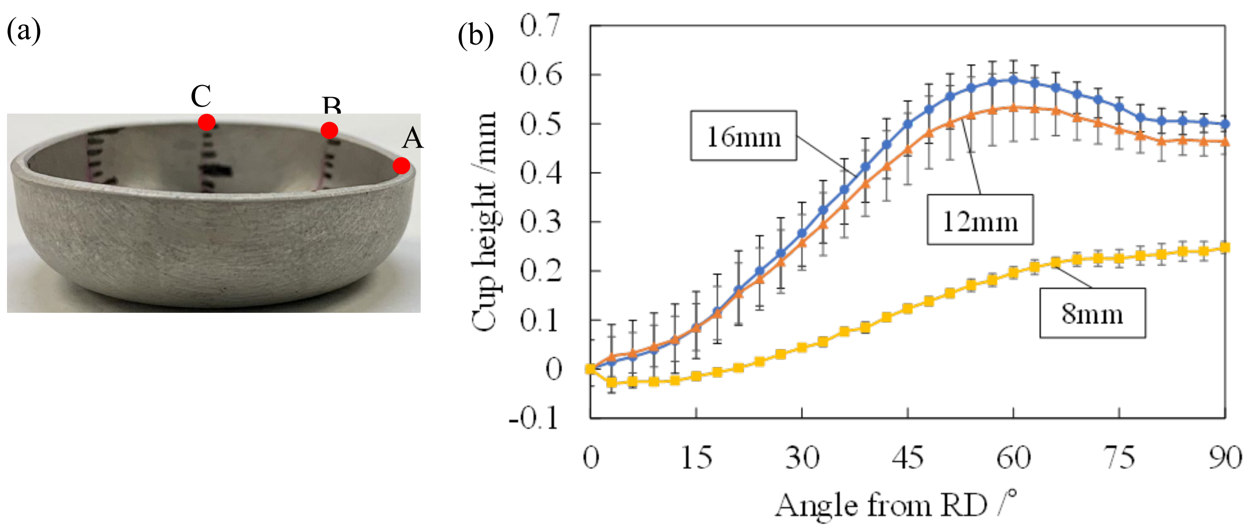

Fig. 3. Geometry of the drawn cup. (a) Photograph of a drawn cup, and (b) distribution of cup height.

resulted in earing formation in the vicinity of the angle of 60°. The tendency of the cup height distribution at the punch stroke of 16 mm remained almost unchanged from that of the punch stroke of 12 mm. It is noted that the cup heights differed largely between the RD and TD also in the final product.

Fig. 4 shows the evolution of thickness strain at the points near the sheet edge in the RD, diagonal direction (DD), and TD, i.e., points A, B, and C in Fig. 3 (a), respectively. The thickness strains increased largely from the punch stroke of 4 mm to 13 mm. The thickness strain was the largest in the RD and that of the DD was larger than that of the TD until the stroke of 13 mm. Thereafter, the thickness strains decreased because of ironing between the punch and the die. Eventually, the thickness strains at the RD and DD became almost the same.

Fig. 5 shows the pole figures measured at the points A and B of the drawn cup. Compared to the initial pole figure shown in Fig. 2, strong peaks near the ND did not appear at both points. In contrast, strong peaks appeared near the TD and RD at the points A and B, respectively. These results show that the texture evolution depended largely on the region.

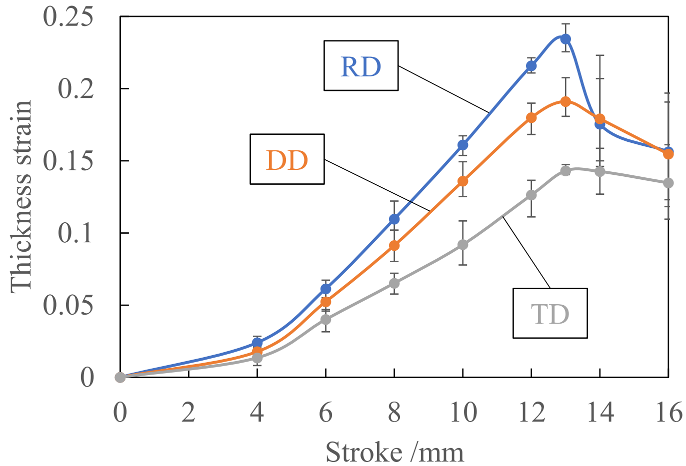

Fig. 4. Evolution of thickness strain at the sheet edge.

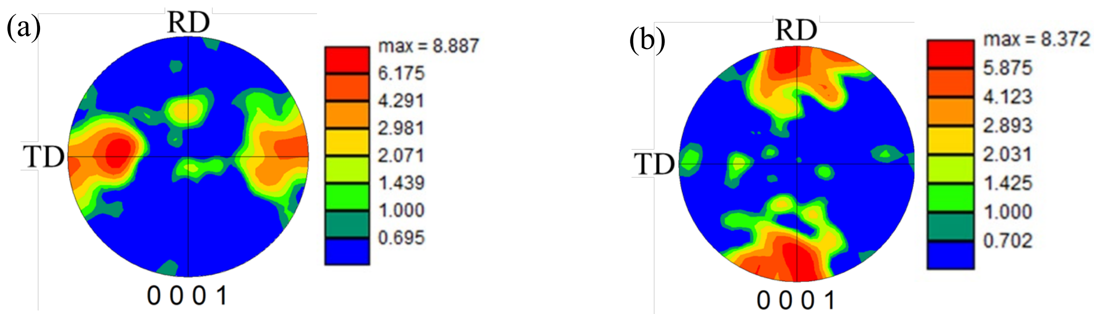

Fig. 5. (0001) pole figures measured at the points (a) A and (b) B.

Results and Discussion

Thickness distributions. The mechanism that the thickness strain was the largest in the RD and the smallest in the TD is discussed. Large thickening occurred at the sheet edge because the sheet edge was subjected to circumferential compression before the sheet edge was drawn into the die cavity. Specifically, during drawing, the regions near the sheet edge in the RD, DD, and TD are subjected to compression in the TD, DD, and RD, respectively. This indicates that thickness increase would be the largest in TD compression and the smallest in RD compression. It may be useful to consider the correlation with Lankford value to examine the difference in thickness increase depending on the direction. However, Lankford values of the Mg alloy sheet would be different between tension and compression because of the polar character of twinning [12]. Therefore, the Lankford values were measured under both tension and compression. In the compression test, comb-shaped dies were attached to the specimen to avoid occurrence of out-of-plane buckling. In both tension and compression tests, longitudinal and width strains were measured using a digital image correlation (DIC) method. In the DIC method, the software GOM Correlate Professional V8 (GOM) was used. Plastic strains were evaluated by subtracting elastic strains estimated using Young's modulus and Poisson ratio from the measured total strains.

Figs. 6 shows the evolution of Lankford values as a function of longitudinal strain. Under tension, the Lankford value was the largest in the RD at small strains, and that in the DD was larger than that of the TD. However, the Lankford values in the DD and TD tended to increase as the strain increased, while the Lankford value in the RD remained almost unchanged; thus, that of the DD became the largest at large strains. Under compression, the Lankford value in the RD was the largest, and that of the DD was larger than that of the TD. This trend remained unchanged in the strain range tested in this work. Apparently, the magnitude relationship of the Lankford value differed between tension and compression. Moreover, the magnitude relationship of the Lankford value under compression at large strains is consistent with that of thickening on the drawn cup before the sheet was subjected to ironing. These results show that, for the ZX10 Mg alloy sheet, the thickness strain distribution should be evaluated not by the Lankford value under tension but by that of compression. Moreover, these results also suggest that the difference in the Lankford value between the RD and TD also yielded the notable difference in the cup height between the RD and the TD.

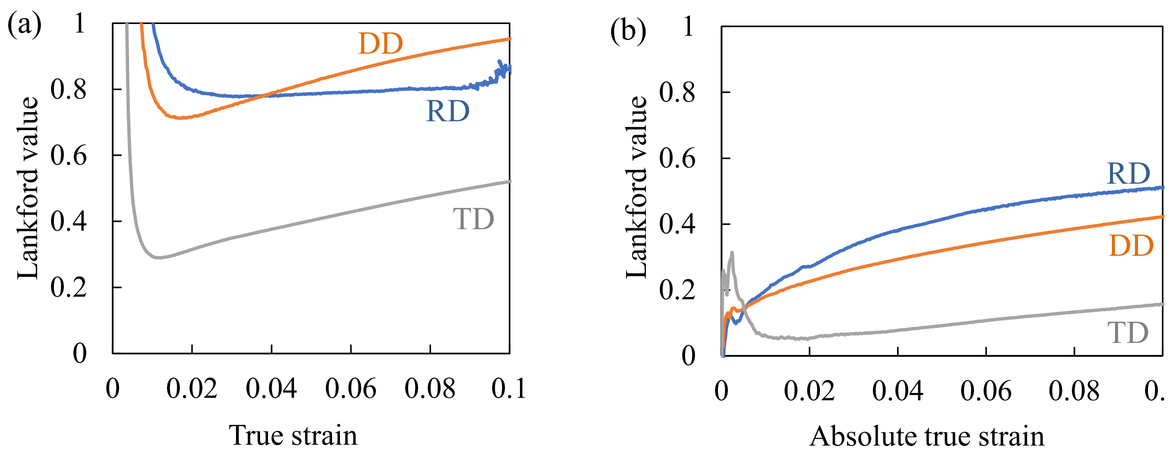

Fig. 6. Evolution of Lankford value under (a) tension and (b) compression.

Texture evolution. Next, the difference in texture evolution depending on the region is discussed. As discussed in a literature [7], under TD compression, twinning is active at the grains whose basal planes oriented near the ND, whereas it is not at the grains whose basal planes oriented near the TD. As a result, the peaks near the ND observed in the initial pole figure tend to disappear and strong peaks appear near the TD. This texture evolution is consistent with that observed at the point A which experienced TD compression

Similarly, under RD compression, twinning is easy to active at both grains whose basal planes oriented near the ND and the TD; thus, the peaks near the TD and ND observed in the initial pole figure disappeared and the peaks near the RD appeared [7]. This is also consistent with the result at the point B.

These results suggest that the texture evolution observed at the sheet edge was primarily governed by circumferential compression and, moreover, one of the reasons that the texture evolution differed depending on the region is the difference in the twinning activity.

Summary

Room-temperature cylindrical cup drawing of a ZX10Mg alloy sheet was conducted and the drawability was discussed. The results obtained in this study can be summarized as follows.

(1) The cup height started increasing largely after the punch stroke exceeded 8 mm. The maximum height appeared at 60° from the rolling direction. The cup height was larger in the transverse direction than in the rolling direction.

(2) The thickness at the cup edge was the largest in the rolling direction and the smallest in the transverse direction before the sheet was subjected to ironing. The magnitude relationship of the thickness correlated with the Lankford values under compression.

(3) The difference in twinning activity was one of the reasons that yielded the difference in the texture evolution depending on the direction.

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