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Observation of Fracture Phenomenon of AZ31 Magnesium Alloy Sheet at Room Temperature

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Abstract

Although Mg alloy sheets are press-formed primarily by a warm forming method, room temperature forming is desired considering the hazards of machining magnesium, deterioration of the lubricants, and energy saving issues. This study investigates the effect of the rolling direction when performing tensile tests and deep drawing experiments. An in-plane compression jig for commercially available AZ31B-O Mg alloy was developed to observe the state when the fracture occurs, and an experiment was conducted. It was observed that the outermost periphery of the flange fractured due to simple compression. The drawability indices, i.e., the tensile strength and n and r values, were 268 MPa, 0.23, and 2.01, respectively, exhibiting larger values than equivalent to those of pure aluminum (A1100P). The elongation to failure is comparatively higher for the case of 45° relative to the rolling direction. In the deep drawing of the Mg alloy, because its the limit drawing ratio (*LDR*) was smaller at approximately 1.5, the deep drawability test cannot be evaluated using the n-value, r-value, or tensile strength, which are the typical parameters for evaluating the acceptability of the deep drawability. An in-plane compression test was conducted on the Mg alloy sheets to obtain the stress-strain curves. These curves indicated that the sheets became plastic at 130 MPa and fractured at 400 MPa. The stress-strain curves verified that the energy up to the point of fracture was lower for in-plane compressive deformation than for uniaxial tensile deformation. Thus, the flange portion was prone to fracture due to compressive deformation. The 30° position relative to the rolling direction was found to be the most vulnerable region against compression. Additionally, the tendency was similar to that in the preceding experiment where the external periphery of the flange was confirmed to fracture at approximately 30° during the deep drawing process.

Keywords: magnesium alloy sheet, sheet metal forming, drawing, fracture locations, in-plane compression test.

1. Introduction

Magnesium (Mg) alloy has attracted much attention since it is the lightest of all practical metals while offering superior specific strength and recyclability[1)]. It is used in the manufacture of laptop computers and automobile parts. Additionally, Mg is not considered as a rare material. However, it is not widely used as a versatile material due to its flammability, difficulties in handling and processing, and high cost. Although Mg alloy sheets are press-formed primarily by a warm forming method, room temperature processing is desired considering the hazard risk, deterioration of the lubricants, and energy saving issues. However, Mg exhibits a characteristic plastic deformation property at room temperature and substantial inferior press formability; consequently, a suitable processing method has not yet been established[2)].

The material property behavior up to the fracture is unpredictable as it deforms, strong anisotropy and rigid texture remain induced by the twinning deformation. For example, when a Mg alloy sheet is deformed by tensile force, a fracture is observed inside of bending where compressive deformation occurs during bending at room temperature instead of outside of bending [3)]. In an experiment where a Mg alloy sheet was formed used a cylindrical deep-drawing process, a fracture was observed at the flange section[4)]. In a similar experiment conducted by the authors, a fracture was observed at the flange edge at an angle of 25° to 30° relative to the rolling direction[5)]. This study hypothesizes that the outermost periphery of the flange fractured due to simple compression. A thin sheet in-plane compression jig was developed to observe the state when the fracture occurs, and an experiment was conducted for commercially available AZ31B-O Mg alloy. Moreover, Tensile and deep drawing of experiments to investigate the effect of the rolling direction.

2. Tensile Properties and Drawability Evaluation

2.1 Test material

The material used in this study is commercially available AZ31B Mg alloy (Mg-3%-1%Zn) sheets, made by OSAKA FUJI Co. Ltd., Japan, with a thickness of 0.8 mm. Table 1 shows the chemical composition. When it is received, it is an AZ31B-O that has been annealed at 360 °C for 1 h to improve the formability and to relieve residual stress of the work hardened AZ31B-H. The microstructure of the equivalent AZ31B-H prior to annealing, as shown in **Fig. 1**(a), is deformed by a rolling processing. An annealing recrystallizes the microstructure exhibiting almost equiaxed grains that are approximately spherical in shape. The grain size number *G* is 11.5, as measured

AMM0012

from the microstructure observed in **Fig. 1**(b) (referred to JIS H0542). The grain sizes ranged from 3 to 20 μm, as shown in the photograph.

Table 1 Chemical composition of material used[wt. %]

Material	Al	Zn	Mn	Si	Fe	Mg
AZ31B-O	2.96	1.03	0.41	0.01	0.001	Bal.

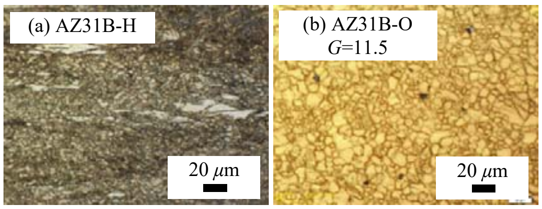


Fig. 1 Microstructures of AZ31B Mg alloy sheet

2.2 Uniaxial tensile properties

Five specimens orientated at 0°, 45° and 90° relative to the rolling direction for the tensile test were sampled to obtain an in-plane anisotropy Δr value. An additional five specimens oriented at 30° and 60° relative to the rolling direction were also sampled to investigate the effect of the rolling direction. The specimens were shaped by an end mill processing in accordance with JIS Z2241-13B. The test was conducted at a tensile speed of 5 mm/min, using an Instron-type universal testing machine TG-50kN (manufactured Minebea).

To obtain the r-value, the test was stopped at 10% of the nominal strain and the sheet thickness, W10%, was measured. **Table 2** shows the uniaxial tensile properties obtained from the tensile test for AZ31B-O. The drawability indices, i.e., the tensile strength, n and r values, were 268 MPa, 0.23, and 2.01, respectively, exhibiting greater than equivalent to those of pure aluminum (A1100P) [6]. **Fig 2** shows stress-strain curves. The elongation to failure is comparatively higher for the case of 45° relative to the rolling direction. The specimens oriented at 0° relative to the rolling direction exhibited slightly higher fracture stress, proof stress, and tensile strength as shown in **Fig. 3.** However, the difference was not significant. This result confirmed that there was no substantial difference in uniaxial tensile properties according to the rolling direction.

Table 2 Uniaxial tensile properties

Sheet thickness, t (mm)	0.8
Young's modulus, E (GPa)	34
Yield stress, Y (MPa)	185
Tensile strength, δ (MPa)	268
Total elongation (%)	26.9
Mean r value $\bar{r}$	2.01
In-plane anisotropy Δr	-0.37
Plastic modulus, F (MPa)	493
Work-hardening exponent, n	0.23
Prestrain, ε_0	0.008

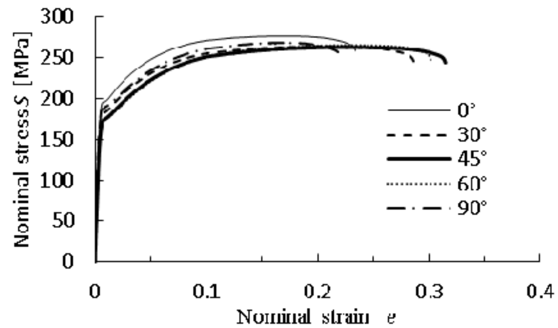


Fig. 2 Stress-strain curve under uniaxial tension

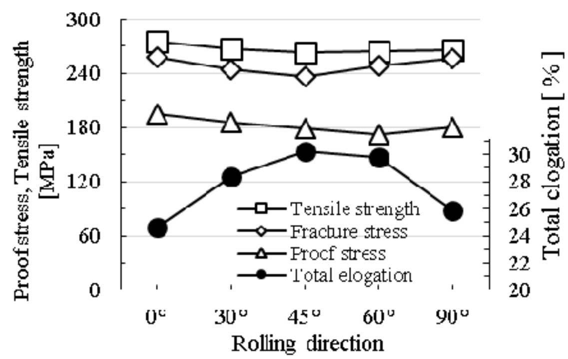


Fig. 3 Effect of rolling direction on uniaxial tensile properties

2.3 Deep drawability

To evaluate the deep drawability of the AZ31-O Mg alloy sheet, a Swift deep drawing test was conducted by the trial load method using an automatic universal draw test machine (Model SAS-12-05 by Tokyo Koki Testing Machine Co., Ltd.). Specifically, the ratio between the thin blank Mg alloy sheet diameter D_0 and punch diameter d_p was designated as the ratio D_0/d_p. The maximum drawable load without fracture and the maximum load when the fracture occurred were plotted. The limit drawing ratio (*LDR*) was determined by intersecting these two lines. **Table 3** shows the dimensions of the punches and dies. A 0.05-mm thick Teflon sheet (PTFE) was stuck on the die side and a 0.05-mm thick PTFE with a hole was stuck on the punch side as lubricant. **Fig 4** shows the limit drawing ratio (*LDR*). The LDR of AZ31B-O was 1.57, almost the same level as that of a typical Mg alloy (about 1.5). The *LDR* of the metallic material having the uniaxial tensile properties shown in Table 2 is known to be approximately 2. In the deep drawing of the Mg alloy. Because its *LDR* was smaller at approximately 1.5, the deep drawability cannot be evaluated by the n-value, r-value or tensile strength which are typically considered to be parameters to evaluate the acceptability of the deep drawability. Therefore, the deep drawability of the Mg alloy is thought to be poor because of the unusual forming crack defects that occur at the flange section.

Table 3 Dimension of punches and dies

Sheet thickness (mm)	Punch		Die	
	Diameter, d_p (mm)	Radius of punch shoulder, R_p (mm)	Diameter, d_d (mm)	Radius of punch shoulder, R_d (mm)
0.8	40	8	42	6

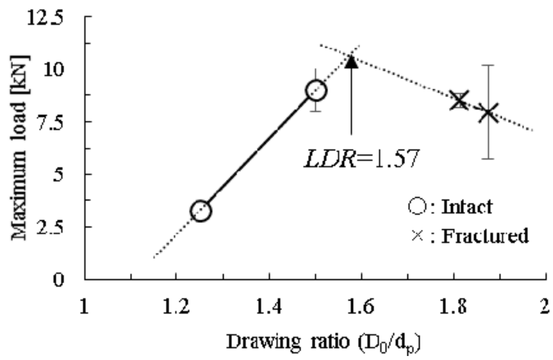


Fig. 4 Determination of Limit drawing ratio

3. In-Plane Compression Test of the Flange Section

3.1 Deep drawability

In this study, the rolling direction of the specimen was designated to be parallel to the horizontal direction as shown in **Fig. 5**. The fracture observed during the deep drawing process initiated at the outermost periphery of the flange at approximately 30° relative to the horizontal direction (rolling direction). Based on this result, the specimens 0°, 30°, 60°, and 90° relative to the horizontal direction were sampled. The specimens for were rectangular with a width of $W = 25$ mm and a length of $L = 50$ mm. The specimens were based on an aspect ratio (L/W) of 2.0 in an attempt to prevent in-plane buckling.

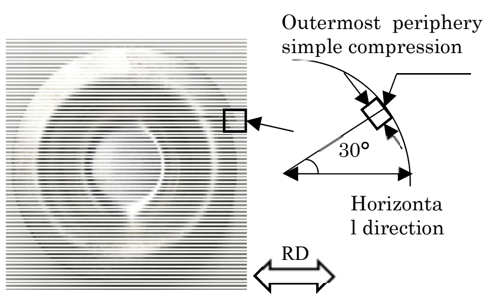


Fig. 5 Fracture developed from the outermost periphery of the flange portion

3.2 Experimental Methods

Fig 6 shows a sketch of the in-plane compression test jig used in the experiment. The dies were made larger than the specimen with a width of 90 mm and an overall length of 160 mm. The dies compress one side of a specimen with a spacer by meshing the comb teeth provided at the ends of male and female dies[7]. The face width of the comb tooth is 4.4 mm with a tooth clearance of 0.3 mm. To ensure the conditions are the same as those for the deep drawing process, the specimen was held in place with a blank holder and the holding pressure on the specimen was adjusted to be applied evenly at approximately 1.33 MPa using bolts and springs. To reduce the friction and to prevent scuffing, petroleum jelly-coated Teflon sheets were inserted between the specimen and the comb-shaped dies.

Fig 7 shows the overview of the in-plane compression jig. The in-plane compression test employed an Instron-type tensile and compression testing machine TG–50kN (manufactured Minebea). A spherical seat was positioned at the head of the test jig to ensure to apply compressive force accurately. The in-plane compression was delivered at a crosshead speed of 1 mm/min. The load was continuously applied until the specimen fractured, at which the load and the displacement were measured.

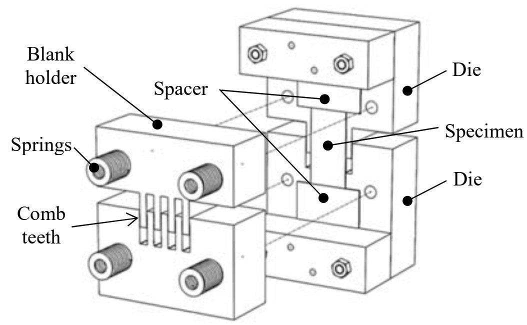


Fig. 6 A sketch of comb shaped dies

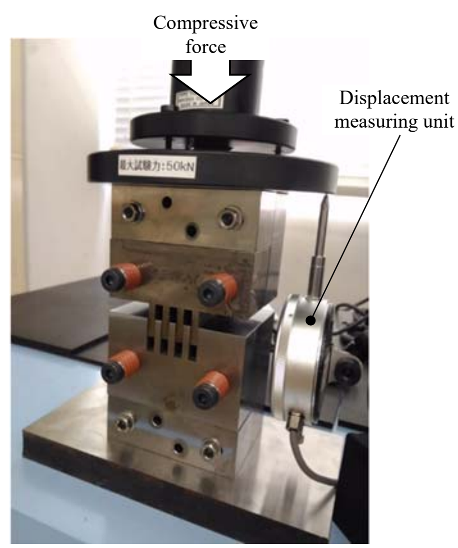


Fig. 7 Overview of the in-plane compression jig

4. Experimental Results and Discussion

4.1 Flange fracture phenomenon due to deep drawing

To investigate the effect of blank holder force (BHF), the drawing ratio was fixed to 2. Additionally, the test was performed by blank holder force at 2 kN and 10 kN. **Fig. 8** shows the exterior views of the fracture location for AZ31B-O by the deep drawing test with the two different blank holder forces. As shown in **Fig. 8**(a) and **8**(b), the fracture in both specimens developed at the external periphery of the flange edge. The different blank holder forces of 2 kN and 10 kN showed no difference in where the fracture developed. When drawing metallic materials such as aluminum or mild steel sheets, increased blank holder force will generally cause the punching force to exceed the wall proof stress of the materials, subsequently the punch shoulder or wall fractures. The fracture starting from the external periphery of the flange as described above may be a fracture form peculiar to Mg alloy. In the deep drawing test, after the predetermined blank holder force was applied, the punch stroke and load up to the fracture point were measured, and the fracture location and the fracture surface were observed.

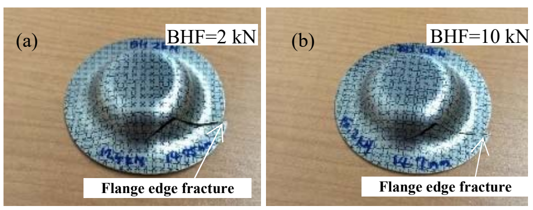


Fig. 8 Exterior views of fracture location after the deep drawing test

The location of the flange edge fracture was consistently oriented at about 30° relative to the rolling direction, as shown in **Fig. 9**. In the drawing, simple compression occurs at the outermost periphery, which is where slipping to the lateral direction starts. The close-packed hexagonal crystal structure of the Mg alloy and the difficulty in increasing the thickness in the direction of sheet thickness are thought to have caused the lateral slipping since lateral slipping requires less initiation energy. The reason for the fracture occurring at the same location is thought to be strongly related to the grade of the close-packed hexagonal structures that are grouped together on the material surface. The effect of temperature on plastic deformation has been reported[8)]. However, the compressive plastic deformation at various temperatures prior to fracture has not been reported, and thus, further detailed clarification is necessary.

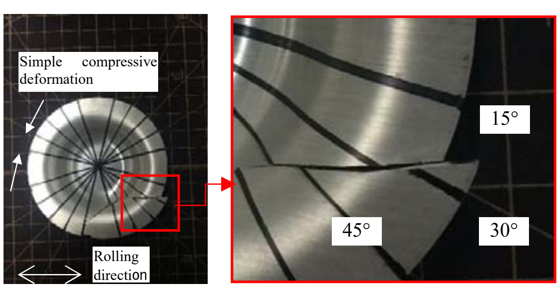
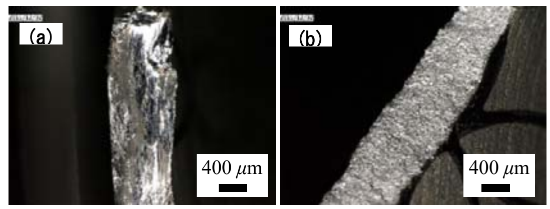


Fig. 9 Enlarged view of fracture

Fig. 10 shows photographs of the flange fracture and the fracture surface of the shoulder fracture magnified by a Wide-Area 3D Measurement System (manufactured KEYENCE). The flange crack surface in **Fig. 10**(a) has glossy properties without unevenness. Thickening the Mg alloy in the thickness direction is difficult due to its close-packed hexagonal structure. The crystals are thought to rotate with the in-plane compressive deformation, causing the lateral slipping. The gloss is probably the product of the lateral slipping at that time. The shoulder fracture surface in **Fig. 10**(b) was unevenly dull. The lateral slipping occurring at the flange portion is thought to have connected to the punch shoulder portion, resulting in the fracture.



(a) Flange crack (b) Shoulder crack

Fig. 10 Photographs of fractured surfaces

4.2 Fracture phenomenon caused by in-plane compressive deformation

Fig 11 shows the location of the fracture surface resulting from the in-plane compression test. The fracture occurred not at the center of the specimen, but at the edge where it contacted the spacer. **Fig 12** is an enlarged schematic view of the positional relationship with the spacer. The spacer pushed the blank holder up, and the edge of the spacer severed the edge of the specimen. It is necessary to improve the dies to let a specimen fracture at its center, which was caused by use of the spacer, rather than at its edge.

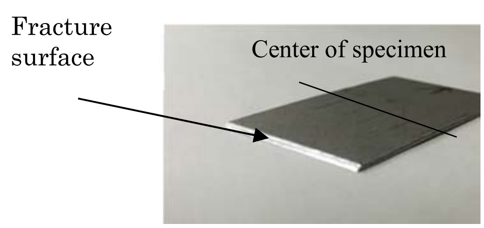


Fig. 11 Location of the fracture surface on the specimen

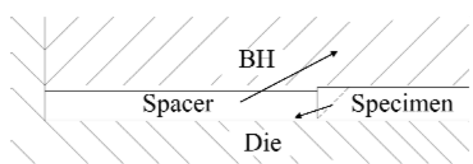


Fig. 12 Positional relationship between fracture surface and spacer

4.3 Stress-strain curve

Fig. 13 shows the stress-strain curves results of the in-plane compression test with the specimen orientated at 0°, 30°, 60°, and 90° relative to the horizontal direction (rolling direction). The uniaxial tensile curves for the specimen oriented at 0°, 45°, and 90° relative to the rolling direction are also shown for comparison. The in-plane compression curves indicate that the plastic region started around 130 MPa, followed by plastic deformation indicated by J-shape, and then the fracture occurred at around 400 MPa. There were no substantial differences in the stress-strain curves according to the angles of orientation, and the rolling direction had little effect on the in-plane compressive deformation. Compared to uniaxial tension test results, the yield stress was lowered by about 30% and the maximum strain by about 50%. These results confirm that the required energy leading up to fracture is lower in in-plane compressive deformation than that in the uniaxial tensile deformation.

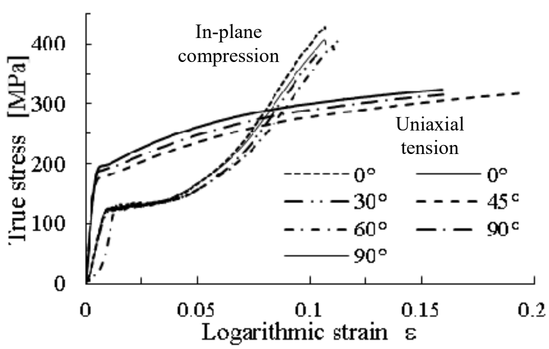


Fig. 13 Stress-strain curves obtained by the in-plane compression test

4.4 Effect of rolling direction

Fig 14 shows the maximum compressive stress in each rolling direction. It indicates that the maximum compressive stress of the specimen oriented at the 30° was the lowest. Therefore, it is possible to conclude that the 0° specimens, which are oriented parallel to the rolling direction, are least likely to fracture, and the specimen oriented at 30° are more likely to fracture. This result is consistent with the findings shown in **Fig. 9** where the fracture occurred around 30° relative to rolling direction, starting from the external periphery of the flange. It is intriguing that the fracture location in the in-plane compression test (the fracture did not occur at the center of the specimen) was consistent with that in the deep drawing test.

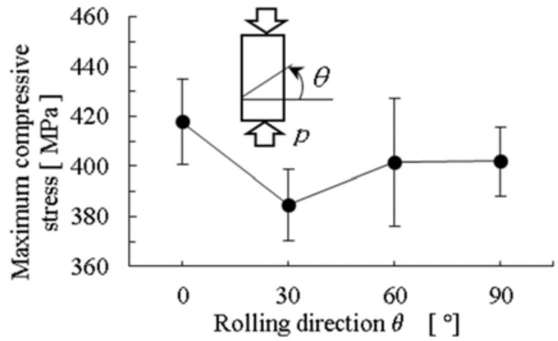


Fig. 14 Effect of rolling direction on the maximum compressive stress

5. Conclusions

An in-plane compression jig was developed to observe the fracture phenomenon of AZ31B-O sheets at room temperature. This study hypothesizes that Tensile and deep drawing of experiments to investigate the effect of the rolling direction. The results of the investigation are summarized below.

(1) The drawability indices, i.e., the tensile strength, n and r values, were 268 MPa, 0.23, and 2.01, respectively, exhibiting greater than equivalent to those of pure aluminum (A1100P). The elongation to failure is comparatively higher for the case of 45° relative to the rolling direction.
(2) In the deep drawing of the Mg alloy. Because its LDR was smaller at approximately 1.5, the deep drawability cannot be evaluated by the n-value, r-value or tensile strength which are typically considered to be parameters to evaluate the acceptability of the deep drawability.
(3) The difference was not significant. This result confirmed that there was no substantial difference in fracture stress, proof stress, and tensile strength of uniaxial tensile properties according to the rolling direction.
(4) These curves showed that the sheets behaved plastic at 130 MPa and fractured at 400 MPa. It is verified that the energy up to fracture was lowered for the in-plane compressive deformation than that for uniaxial tensile deformation. Thus, the flange portion was prone to fracture due to compressive deformation.
(5) The specimen oriented at 30° position relative to the rolling direction was found to be the most vulnerable against compression. Additionally, the tendency was similar to that in the preceding experiment where the external periphery of the flange was confirmed to fracture at around 30° in deep drawing.

7. References

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