Stress and Strain Behaviors of Mg Alloy AZ31 in Plane Strain Compression*

Ikuo YARITA**, Takashi NAOI*** and Tsuyoshi HASHIZUME***

Most of magnesium alloy products are manufactured by die casting or thixo-molding processes. However, there is extremely little use of the products by metal forming due to high resisting plastic deformation in normal temperature and their expensive cost. In this study, to make clear the plastic deformability, stress and strain behaviors of Mg alloy AZ31 hot rolled sheet in plane strain compression in the temperature from 20°C to 250°C have been discussed. Tension test and plane strain compression test have been performed to obtain the equivalent stress and equivalent plastic strain relations. The plane strain compression tests with some lubricants have been performed, and the effect of friction between die and deforming material on plastic deformation behaviors has been investigated by the elastic-plastic finite element analysis. Optical microstructures of deformed materials are also observed.

Key Words: Magnesium Alloy AZ31, Plastic Deformation, Stress and Strain, Plane Strain Compression

1. Introduction

There are many demands for magnesium alloys to employ the automotive parts and electric products due to Mg alloys have many profitable properties such as small specific gravity, high specific strength, vibration absorption and EMI shielding. However, most of Mg alloy products are manufactured by die casting or thixo-molding processes. There is extremely a little use of the products by metal forming except for electronic machine part's cases, which caused from high resisting plastic deformation in the normal temperature, poor anti-corrosiveness⁽¹⁾ and their expensive cost. To expand the products by metal forming, the efficient rolling technology to obtain thin sheet products having high mechanical properties and surface quality is required. Thus, the optimum sheet forming technology should be established. However, a few technical information of metal forming as rolling and sheet forming for Mg alloys⁽²⁾⁻⁽⁵⁾ has been described.

In this study, stress and strain behaviors of Mg alloy AZ31 hot-rolled sheet in plane strain compression in the

temperature from 20°C to 250°C have been discussed^{(6),(7)} to make clear the plastic deformability. Tension test and plane strain compression test have been performed to obtain the equivalent stress and equivalent plastic strain relations. The plane strain compression tests with some lubricants have been performed, and the effects of friction between die and deforming material on plastic deformation behaviors are investigated by the elastic-plastic finite element analysis.

2. Stress and Strain Behaviors

2.1 Specimen

Hot-rolled sheets of magnesium alloy AZ31 have been employed. Table 1 shows chemical compositions, and Fig. 1 shows microstructure of the sheet for tensile and plane strain compression tests. Mean grain size is about 11 μm .

2.2 Tensile test

Uni-axial tensile tests have been conducted under the conditions in the temperature from the normal temperature (20°C) to 250°C, and the strain rate from 4×10^{-4} to 4×10^{-2} . Figures 2 and 3 show experiment results for effects

Table 1 Chemical compositions of AZ31 sheets(mass%)

Al	Zn	Mn	Fe	Si	Cu	Mg
2.5 ~3.5	0.6 ~1.4	0.20 ~1.0	0.005	0.10	0.005	Bal.

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** Department of Mechanical Science & Engineering, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan.

E-mail: yarita.iku@it-chiba.ac.jp

*** Graduate Student, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan

Fig. 1 Microstructure of hot-rolled AZ31 sheet

Fig. 2 Effect of temperature on 0.2% proof stress, tensile strength and elongation

Fig. 3 Effect of test speed on 0.2% proof stress, tensile strength and elongation

of temperature and test speed (strain rate) on 0.2% proof stress, tensile strength and elongation respectively.

Fig. 4 Apparatus for the plane strain compression tool

Table 2 Specification of test die tool

Material	SKD61
Size	a=8, b=50, h=2.5, w=80, l=80[mm]
Heater	200V, 75W×8

Fig. 5 Relation between mean pressure and strain in plane strain compression

With the temperature rise, the proof stress and tensile strength decrease, and elongation increases as shown in Fig. 2. It is supposed that plastic deformability is drastically improved above 200°C. However, with the temperature rise, the test speed (strain rate) so affects on the proof stress, tensile strength and elongation that stresses becomes higher and elongation smaller.

2.3 Plane strain compression

In the metal forming processes, plane strain deformation has been much observed. Thus, the plane strain compression tests have been performed and the stress and strain behaviors are compared with that by the uni-axial tensile test. The dies install bar heaters embedded as shown in Fig. 4 and Table 2. The die temperature is able to be raised up to 250°C. To neglect the friction between dies and deforming material, the grease contained Mo is employed as lubricant.

Figure 5 shows the relation between the mean pressure and true strain obtained by the plane strain compression.

Fig. 6 Microstructures of deformed materials after plane strain compression

sion test. Below the temperature of 100°C, the pressure rapidly increases with small strain and it shows poor deformability. However, at 200°C, the material shows good deformability with smaller pressure, so that large compressive strain as more than 1.3 can be obtained without failure. Figure 6 shows the microstructures of deformed materials after the compression at each temperatures and strains. In the normal temperature and 100°C, twin deformation in a fine crystal may be observed, but at 200°C, grain growth has occurred due to dynamic crystal recovery or dynamic re-crystallization during compression, which causes good deformability.

Figure 7 shows comparison of the equivalent stress-equivalent plastic strain curves in the tension and the plane strain compression. In the normal temperature and 100°C, elongation in the tension is a little larger than that in the compression, but at 200°C, the result in the compression shows larger elongation. In small strain at the beginning of deformation, yield stress in the compression is smaller. However, as strain increases, yield stress becomes larger than that in the tension.

Figure 8 shows comparison of microstructures of deformed materials between the tension and the compression at the plastic strain of 0.02. Twin deformation in the compression is more observed than that in the tension, which

Fig. 7 Equivalent stress-equivalent plastic strain curve in tension and plane strain compression

results in smaller yield stress at the beginning of deformation in the compression.

3. Plane Strain Compression

To assure the effects of friction between die and deforming material on plastic deformation behaviors, the plane strain compressions with some lubricants have been performed.

Fig. 8 Microstructures of deformed sheets at the plastic strain of 0.02

Table 3 Properties of lubricants

	Gravity (g/cm ³ at 15°C)	Viscosity (mm ² /s at 40°C)
Mineral oil	0.87	90.5
Synthetic ester A	0.86	6.70
Synthetic ester C	0.90	1110.0
Dry (no lub.)	—	—

3.1 Experiment condition

In the experiment, material to be deformed and compression tool are employed as same as mentioned above. Three kinds of lubricants are employed as shown in Table 3. Two synthetic esters with different viscosities are prepared in the experiment to make clear the effect of lubricant on deformability. Mineral oil is normally used in sheet rolling of Mg alloys, and synthetic esters are employed in aluminum and steel sheet rolling. Temperatures of both material and tool dies are set from room temperature to 250°C in the experiments.

3.2 Experiment results

Figure 9 shows the relation between the mean compressive pressure and true strain in each experiment temperature. In the normal temperature and 100°C, lubricant shows a little effect on the deformability, and at 200°C, lubricant remarkably improves the deformability. Especially, synthetic esters A and C provide larger plastic strain with small compressive pressure.

However, when the temperature rises to 250°C, lubricants have no effect on deformability, and the mean pressure are coincide with that in dry friction. It may be caused by vaporization of lubricants around 250°C.

Figure 10 shows microstructures of deformed materials in the plane strain compression at the temperature of 200°C, comparing between dry (without lubricant) and lubricated (with ester A) frictions. The material compressed with dry friction shows less uniform microstructure in the thickness direction than that of the material with lubricant. The structure of the deformed material with dry friction

Fig. 9 Effect of lubricants on mean pressure and strain relations in plane strain compression

has larger grain around the surface, and fine and coarse grains coexist at the center in the thickness. The structure of the material with dry friction is larger than that with lubricant at the surface contacting with die, due to the so-called un-deformed dead metal.

4. Discussion

Effect of friction between die and deforming material on plastic deformation behaviors of the material in the plane strain compression has been discussed. Stress and strain in the deforming materials are analyzed by the elastic-plastic FEM employing the ANSYS code. The equivalent stress and equivalent plastic strain relation in the compression analysis is employed the relation as shown in Fig. 7.

Fig. 10 Microstructures of deformed materials in plane strain compression at temperature 200°C comparing between dry (without lubricant) and lubricated (with ester A)

Fig. 11 Effect of friction coefficient on mean compressive pressure and true strain obtained by EP-FEM and by experiment of plane strain compression

Figure 11 shows relation of the mean compressive pressure and true strain according to friction coefficients comparing between that calculated by the elastic-plastic finite element method and that obtained by the experiment at the temperature of 200°C. The relation without lubrication (dry) roughly coincides with $\mu = 0.3$, and the relation with ester A coincides with $\mu = 0.1$ respectively.

Figure 12 shows the equivalent plastic strain distributions calculated by the elastic plastic finite element analysis employing the ANSYS code. The strain distribution with dry friction supposing friction coefficient of $\mu = 0.3$ is less uniform in the thickness direction than that with lubrication supposing $\mu = 0.1$. Larger equivalent plastic strain

Fig. 12 Equivalent plastic strain distributions calculated by EP-FEM (reduction=30%)

arises at the center of material in thickness. The surface of deforming materials at the center of die have small strain, and the un-deformed dead metal is observed at directly under the center of die in the case of $\mu = 0.3$. The difference of uniformity of strain distributions between frictions causes to the difference of the microstructure in the thickness direction as shown in Fig. 10.

5. Conclusion

Stress and strain behaviors of Mg alloy AZ31 hot-rolled sheet by the uni-axial tension and by the plane strain compression tests in the temperature from 20°C to 250°C have been discussed. The plane strain compression tests with some lubricants have been performed. Then, the effects of friction between die and deforming material on plastic deformation behaviors are investigated by the compression tests and by the elastic-plastic finite element analysis. The results obtained are as follows;

(1) The material shows good deformability above the temperature of 200°C, so that large compressive strain may be obtained without failure.

(2) In small plastic strain region, the yield stress in compression is smaller, and with strain increase, the yield stress becomes larger than that in tension.

(3) At 200°C, lubricants remarkably improve deformability of the material. However, as the temperature arises to 250°C, lubricants have no effect on deformability due to their vaporization.

(4) The strain distribution with dry friction is less uniform in the thickness direction than that with lubrication. Thus, the material compressed with dry friction

shows less uniform microstructure in the thickness direction than that of the material compressed with lubricant.

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