Fracture Mechanism and Forming Limit in Deep-Drawing of Magnesium Alloy AZ31

Masahide Kohzu, Fusahito Yoshida, Hidetoshi Somekawa,*, Masahiro Yoshikawa,*, Shigenori Tanabe and Kenji Higashi

Department of Metallurgy and Materials Science, College of Engineering, Osaka Prefecture University, Sakai 599-8531, Japan
Department of Mechanical Engineering, College of Engineering, Hiroshima University, Higashihiroshima 739-0006, Japan

A fracture mechanism and forming limit in cylindrical deep-drawing below 473 K was investigated for commercially rolled sheet of magnesium alloy AZ31. A small punch radius, of which the ratio to thickness was 2.5, was adopted intentionally. At room temperature, a brittle fracture under a very small punch load occurred at an early stage on the punch shoulder near the bottom. It was confirmed by stretch bending tests that the fracture was caused by bending under high tension, which deeply concerned with high yield stress and little local elongation of this material. The forming limit was dominated by this mechanism up to 453 K in semi-static drawing.

(Received January 22, 2001; Accepted May 25, 2001)

Keywords: magnesium alloy; fracture mechanism, forming limit, rolled sheet, deep-drawing, punch radius, stretch-bending, room temperature, local elongation

1. Introduction

A number of magnesium alloys exhibit excellent mechanical properties, such as high specific strength at room temperature. In addition, there are many potential opportunities for the use of magnesium alloys in motor vehicle components. This is based not only on magnesium's relatively low density, which can directly and substantially reduce vehicle weight, but also on its good damping characteristics, dimensional stability, machinability, and low melting costs. These desirable attributes enable magnesium alloy products to economically replace many zinc and aluminum die casting, as well as cast iron and steel components and assemblies for motor vehicles.

On the other hand, magnesium alloys normally exhibit limited ductility because of their HCP structure. It is, therefore, difficult to manufacture structural components with a wrought alloy which generally exhibits a higher fracture toughness than the casting alloy. Recently, the plastic forming of magnesium alloy can be greatly improved by their structure control for superplasticity at elevated temperatures of 0.8Tm, where Tm is the melting point of material. Superplastic forming and injection molding, etc. are viable techniques to fabricate a hard-to-form material into complex shapes.

In the future, demand of magnesium alloy as structural material is expected to expand drastically from the problems of energy and environment. Then, shift from die-casting to press-forming should be considered in order to obtain shell structure with high productivity and quality. Limited data are, however, available for the press-forming of magnesium-alloy sheets, and are not enough to give a guideline for practical manufacture or for improvement in formability. In this study, the fracture mechanism and forming limit has been investigated under following conditions; in cylindrical deep-drawing with a small punch radius, use of an only commercially rolled sheet, AZ31, and at low temperatures near the room temperature.

2. Experimental Procedures

The material used in this study was AZ31 received in the form of a commercially rolled sheet of 0.8 mm in thickness. The chemical composition was Mg-3.0 mass% Al-1.0 mass% Zn. The material was annealed at 673 K for 1.8 ks before several tests in order to homogenize and to remove the strain by leveling. The average grain size was about 20 μm, which was almost equal to that before annealing. A typical microstructure of the annealed material is shown in Fig. 1.

Tensile tests at a room temperature (about 300 K) were carried out under strain rates of 1.0 x 10^{-3} s^{-1} and 1.0 x 10^{-1} s^{-1} with the specimens of 6 mm in width and 18 mm in gauge length.

Cylindrical deep-drawing tests at a room temperature ~473 K were carried out under drawing rate of ~500 mm/min under lubrication by Molybdenum-

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*Graduate Student, Osaka Prefecture University.

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Fig. 1 Microstructure of AZ31 rolled sheet annealed at 673 K.
disulphuride paste kneaded with silicon-oil. The apparatus was in a furnace and was loaded by multi-testing-machine as shown in Fig. 2. The forming image using the tools with standard dimensions is shown in Fig. 3. A punch radius, whose ratio to thickness is small at 2.5, is adopted intentionally, because it has been known experimentally that forming into gently curved surface is relatively easy.

Blanking tests and stretch-bending tests\(^{10}\) were carried out to verify the fracture mechanism in this deep drawing. In the blanking tests, the deep-drawing apparatus is used and the corner punch and die are prepared. The die hole diameter is determined, as clearance with punch is 0.1 t, where t is the thickness of blank. In addition, the die of 1.2 t in clearance and the tools (both punch and die) having small profile radius of 1.0 mm were prepared for the medium tests between blanking and deep-drawing. In the stretch-bending tests, strips of 20 mm in width were bent along a die by stretching with the constant stress rate of 1.17 MPa s\(^{-1}\) (nominal) after pre-stretching at initial stress of 11.7 MPa from a loosened state. The die radius is made equal to the standard punch radius used in deep-drawing. The stress rate is made equal to the maximum stress rate under drawing ratio of 1.67 at 413 K which is the middle temperature in warm drawings.

3. Experimental Results and Consideration

3.1 Tensile tests

Nominal stress-nominal strain curves of used AZ31 alloy sheets are shown in Fig. 4. At room temperature, the received sheet shows some degree of elongation, but breaks in a flash without necking. Though the total elongation is more than 20% by annealing, little local elongation indicates that the local fracture strain is far smaller than ductile materials such as mild steel. This result is very important on discussion about formability of this alloy. By heating at relatively low temperature of 373–473 K, ductility is improved remarkably, which is caused by rapid reduction of critical shear stresses on non-basal planes of the HCP crystal. With elevating temperature, strain rate sensibility appears but is not so large as in superplasticity.

The flow stress (true stress) and elongation at true strain rate of $1 \times 10^{-2}$ are varied with elevating temperature as shown in Fig. 5. The flow stresses for several temperatures are the values at a true strain of 0.2. The $n$-value and $r$-value are varied with elevating temperature as shown in Fig. 6. These results indicate that too high temperatures are not suitable for deep drawing. As explained later in detail, the fracture style in deep-drawing which is peculiar to this material changes to usual fracture caused by thickness necking on punch shoulder above a certain temperature. A limiting drawing ratio (LDR) will be increased by the improvement in ductility with elevating temperature, but above this temperature, will be decreased by the reduction in $n$-value and $r$-value, especially $r$-value.
3.2 Deep-drawing tests

The drawing rate, which is crosshead speed of multi-testing machine shown in Fig. 2, was fixed at 5 mm/min except for the investigation on effects of itself. This velocity can be converted into an average equilibrium-strain rate in flange, and the value is about $6 \times 10^{-3}$ s$^{-1}$.

The blanks drawn at room temperature break easily under a low punch load at early stage as shown in Fig. 7. In this figure, lefts are formed from received sheet without annealing. The fracture in as-received sheet is characterized by the position near the cup bottom as illustrated in Fig. 8. It approaches a little to usual fracture position in deep-drawing by annealing, and reached there with elevation in forming temperature.

Effect of temperature on LDR is shown in Fig. 9 and the products of several drawing ratios are shown in Fig. 10. The maximum LDR of 2.2 is obtained at 453 K, at which the fracture with thickness necking indicates a sufficient ductility of this material. Heating over this temperature cannot improve LDR because of reductions in $n$-value and $R$-value as described above.

Effects of drawing rate at $DR = 1.67$ on drawable temperature and the maximum stress through a drawing process are shown in Fig. 11, where the maximum stress is the non-

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Fig. 6 Effects of temperature on $r$-value and $n$-value in AZ31 alloy.

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Fig. 9 Effect of temperature on limiting drawing ratios (LDR).

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Fig. 10 Products of several drawing ratios.

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Fig. 11 Effects of drawing rate on drawable temperature and maximum stress ($DR = 1.67$).

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Fig. 7 Blanks drawn at room Temperature.

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Fig. 8 Illustration of characteristic fracture position in deep-drawing of AZ31 alloy at room temperature.
Changes of nominal fracture stress $F_T/S$ in the stretch-bending tests with elevating temperature is shown in Fig. 13, where $F_T$ is tension applied to strip (specimen) and $S$ is its initial sectional area. The nominal fracture stress increases acutely in elevating temperature and reaches to a peak at $373\,\text{K}$, then turned to a decrease. Above $373\,\text{K}$, some degree of whole elongation was recognized. Less than it, it is considered that the surface stress at tensile side reached to the local fracture stress (true stress) before elongated wholly. This temperature corresponding to the peak is nearly equal to drawable temperature under the drawing ratio of 1.67. Of course, it is not transition temperature from brittleness to ductility and will be shifted by loading rate (stress rate) or die radius, which should be investigated hereafter.

From above results, it is clarified that forming limit in deep-drawing of magnesium alloy AZ31 can be determined by whether the maximum stress required to draw a flange into the die hole exceeds the fracture stress in stretch bending test at the same loading rate.

4. Conclusion

The fracture mechanism and forming limit in deep-drawing of magnesium alloy AZ31 has been investigated. The results are summarized as follows.

1) Heating from 373 to 473 K produces remarkable improvement in ductility.
2) The maximum LDR of 2.2 was obtained at 453 K under semi-static drawing rate of 5 mm/min (punch diameter: 15 mm).
3) The drawable temperature increases with an increase in drawing rate.
4) The fracture in deep-drawing is caused by stretch bending under high tension on a punch shoulder.

REFERENCES