Anisotropy and Non-Uniformity in Plastic Behavior of AZ31 Magnesium Alloy Plates

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On the AZ31-O magnesium alloy plates of 20 mm in thickness, basal plane texture was studied for the samples taken from different layers. Compression tests were carried out in the rolling, width and thickness directions at room temperature. Tensile tests were conducted for the specimens taken from the different layers of the plates in different planar directions. The formability in deep drawing and stretch forming was evaluated for the thin sheet specimens taken from different layers of the plates and the results were discussed in relation to the texture and mechanical properties. The severity of the basal plane texture is higher at the surface layer than the inner layers. In tensile tests at room temperature, proof stress is higher for the surface layer than the inner layers, whereas elongation is lower and r-value is higher at the surface layer. In compression tests at room temperature, yield stress in the rolling and width directions is appreciably lower than in the thickness direction. At 573 K, anisotropic and non-uniform deformation behavior disappeared. Thin sheet specimens taken from inner layers of the plates showed higher formability than those from the surface layer in deep drawing and stretch forming. It is concluded that the formability of magnesium alloy sheets can be improved by decreasing the severity of the basal plane texture.

1. Introduction

In rolling of magnesium and its alloys, the basal plane of the hexagonal lattice becomes aligned parallel to the sheet plane so that a strong basal plane texture is formed. Such textures are maintained even after recrystallization by annealing. Thus, rolled sheets of magnesium and its alloys generally show a strong anisotropy in plastic deformation behavior at around room temperature. Deformation accompanying with thickness reduction is always difficult, that is, they show low limits of plastic deformation in cold rolling and in sheet metal forming. This is the main reason why the rolled sheets of magnesium and its alloys are not widely used in practice in spite of the recent high demands for the lightweight materials. However, high plastic anisotropy of magnesium alloy sheets becomes disappeared at temperatures above 473 K due to contribution of non-basal plane slip systems. At these temperatures, sheet rolling of magnesium alloys becomes much easier and the formability in deep drawing,\(^1\)\(^\text{-}\)\(^3\) stretch forming,\(^4\)\(^\text{-}\)\(^5\) bending\(^5\) and forming limit curves\(^6\) is appreciably improved.

In thick plates of magnesium alloys, basal plane texture is considered to be less developed than in thin sheets due to lower reduction and higher rolling temperature. Additionally, mechanical properties in the thickness direction can be evaluated in thick plates. The anisotropy and non-uniformity of the basal plane texture and mechanical properties can also be discussed by testing specimens from the different layers of the plates. Obtained results are considered to suggest the desirable textures and mechanical properties for higher formability at room temperature. It has been reported in plane strain compression tests of AZ31 magnesium alloy plates that the compressive yield stress in the rolling direction is appreciably lower than in the other directions, which can be attributed to the highly developed basal plane textures.\(^7\) However, very little has been known on the plastic behavior of magnesium plates. It is the purpose of this work to elucidate the anisotropy and non-uniformity of plastic behavior of the magnesium plates.

In this work, the basal plane texture was studied for the samples taken from different layers of AZ31-O magnesium alloy plates of 20 mm in thickness. Compression tests were done in the rolling, width and thickness directions at room temperature. Tensile tests were conducted for the specimens taken from the different layers of the plates in different planar directions. Finally, formability in deep drawing and stretch forming was evaluated for the thin sheet specimens taken from different layers of the plates and the results were discussed in relation to the texture and mechanical properties.

2. Experimental Procedure

Rolled plates of O-tempered AZ31 magnesium alloy of 20 mm in thickness and 1200 mm in width produced by Spectrulite Consortium. Inc. of U.S.A. were used as the test material. Specimens for texture measurements were taken from the different layers of the plates, that is, the surface layer (S-layer), the center layer (C-layer) and the layer (Q-layer) in between S-layer and C-layer. For each specimen, the (0001) pole figure was obtained by the Schulz reflection method using a Rigaku X-ray diffractometer with a Rigaku pole figure unit. The area of the specimen surface used for pole figure determination corresponded to a circle of 34 mm in diameter. Optical microstructures were also examined for the specimens taken from the different layers of the plates.

Tensile test pieces of 3 mm in thickness were taken from three different layers of the plates: S-layer (0–3 mm from the plate surface), C-layer (8.5–11.5 mm from the plate surface) and Q-layer (3.5–6.5 mm from the plate surface). Tensile direction was set in the directions 0\(^\circ\), 45\(^\circ\) and 90\(^\circ\) to the rolling direction and the planar anisotropy was examined. The parallel part of the tensile specimen was 60 mm long and 12.5 mm wide. Tensile tests were conducted at a rate of 0.05 mm/s at room temperature, and proof stress, tensile strength, elongation and r-value (Lankford value)
were obtained as the average values of triplicate tests.

Cylindrical compression test pieces of 10 mm in diameter and 18 mm in length were prepared in the compressive direction parallel to the rolling direction (RD), width direction (WD) and thickness direction (TD) of the plates. Tests were performed at room temperature, 373, 473 and 573 K, and at a compressive rate of $8.3 \times 10^{-3}$ mm/s, and the compressive yield stress, compressive strength and compressive fracture strain were obtained as the average of triplicate tests. In high temperature tests, the specimens were held at the test temperature for 300 s before starting the compression tests. Teflon film of 0.1 mm in thickness was inserted between the test piece and tool surface as the lubricant. Changes of the specimen shape and dimensions were measured by interrupting the compression test at various stages.

Thin sheet blanks of 1 mm in thickness for the formability tests were prepared from the three different layers of the plates, i.e., S-layer (0–1 mm from the plate surface), C-layer (9.5–10.5 mm from the plate surface) and Q-layer (4.5–5.5 mm from the plate surface). In order to evaluate the drawability, circular blanks of 50 mm in diameter were used for the conical cup tests performed in accordance with JIS Z 2249. The tests were performed at room temperature at a punch speed of 0.1 mm/s, and the limiting values of drawing ratio were determined. Furthermore, circular blanks of 75 mm in diameter were prepared for the Erichsen tests (JIS Z 2247) in order to examine stretch formability. Erichsen tests were done at room temperature at a punch speed of $1.7 \times 10^{-2}$ mm/s. In the formability tests, Teflon film of 0.1 mm in thickness was applied between the blank and punch as the lubricant. The forming limit values of the conical cup and Erichsen tests were represented by as the average of triplicate tests.

3. Results and discussion

3.1 Structures and textures

Optical micrographs of the samples taken from three different layers of the plates are shown in Fig. 1, which shows the structures on the plane parallel to the plate surface. The equiaxed grain structures of the average grain size of about 40 μm were observed for all the layers. However, the scattering in grain size is larger for S-layer whereas grain size is more uniform for the inner layers. Observation of each layer on the planes normal to the plate surface revealed nearly the same equiaxed grain structures as on the parallel plane, and hence the tested plates of AZ31-O showed three-dimensionally equiaxed grain structures.

Obtained (0001) pole figures of three different layers of the plates are shown in Fig. 2. Each layer clearly shows that basal planes of the hexagonal lattice tend to be aligned parallel to the plate surface, i.e., formation of the basal plane texture. However, the severity of the basal plane texture is highest for S-layer and becomes appreciably lower for inner layers. The texture severity of C-layer is nearly the same as that of Q-layer. The X-ray diffraction intensity from the basal plane is shown against the angle $\alpha$ in Fig. 3 for each layer of the plate. Here, $\alpha$ is the angle between the normal to the basal plane and the plate plane. Since the basal plane is most likely aligned parallel to the plate plane, X-ray intensity is the highest at $\alpha = 90^\circ$. The basal plane texture of AZ31 magnesium alloy plate is clearly more severe in the surface layer than inner layers. This fact, which has been reported earlier, can be attributed to lower rolling temperatures at the plate surface caused by heat conduction from the plate to the working rolls and to higher deformation constraint near the surface during hot rolling.
3.2 Tensile deformation

Tensile properties at room temperature of different layers of the AZ31 plates are shown in Figs. 4 and 5. The proof stress shown in Fig. 4(a) is higher for S-layer because of higher accumulation of the basal plane texture and hence higher Taylor factor. The proof stress is also higher in the direction 90° to the rolling direction. Tensile strength in Fig. 4(b) is nearly the same regardless of the different layers and tensile directions. This is possibly because larger work hardening as well as larger elongation was observed under the condition of lower proof stress whereas lower elongation and smaller work hardening for higher proof stress.

Elongation shown in Fig. 5(a) is lowest for S-layer and highest for C-layer in all tensile directions. Thus, elongation increases with the distance from the surface of the plates. S-layer shows the highest proof stress and lowest elongation, whereas inner layers show lower proof stress and higher elongation. It follows that accumulation of the basal plane texture increases the proof stress but decreases elongation. As for the tensile direction, elongation is lower and proof stress is higher for all layers in the direction 90° to the rolling direction of the plates. The Lankford value (r-value) shown in Fig. 5(b) is largest for S-layer and lowest for C-layer. The average r-values of three different tensile directions are 2.2 for S-layer, 1.8 for Q-layer and 1.7 for C-layer. Thus, plastic anisotropy as well as the severity of the basal plane texture is
highest at the surface layer of the plates and decreases with increasing the layer depth.

3.3 Compressive deformation

True stress-true strain curves in compression tests at room temperature are shown in Fig. 6. In order to compare plastic deformation behavior between compression and tension, a typical stress-strain curve in tensile tests, that is, a true stress-true strain curve for S-layer in the direction 90° to the rolling direction is inserted in this figure. In compressive deformation, a stress-strain curve in the thickness direction of the plates is apparently different from those in the rolling and width directions. But, it is similar to that in tensile test. In case of compressive deformation in the direction parallel to the plate surface, that is, in the rolling and width directions, clear yielding is observed at appreciably lower stress, but compressive stress increases at higher strain due to remarkably high strain hardening. Thus, compressive stress becomes more or less the same for all directions at higher compressive strain. Compressive fracture strain is lower in the thickness direction.

When compressive stress-strain curve in the width direction is compared to tensile stress-strain curve in the same direction (Fig. 6), yield point is not observed in tension and the yield stress in compression is appreciably lower than the proof stress in tension. However, stress levels at higher strain are similar due to larger strain hardening in compression and the maximum true stress values in compression and tension are nearly the same. Such difference in proof stress between tension and compression in magnesium plates has been reported in an earlier paper, and has been attributed to (1012) twinning observed only in compression.

In case of high temperature compression tests, fracture strain was not well-defined and hence tests were discontinued after observing a definite decrease in flow stress. True stress-true strain curves in compression tests at 473 K are shown in Fig. 7. Yield point is clearly observed in both rolling and width directions in the same way as at room temperature. The difference in the stress-strain curve between the thickness direction and the other directions remains noticeable. However, the compressive stress-strain curves at 573 K, shown in Fig. 8, are nearly the same for all the test directions. Hence, the plastic anisotropy in compression becomes disappeared at this temperature. It has been reported in AZ31 magnesium sheets that the Lankford value approaches to 1 at 573 K.

Changes in specimen outer shapes during compressive deformation have been studied in relation to plastic anisotropy. In case of compression in the rolling and width directions, the cross section of the cylindrical specimen was

![Fig. 5 Elongation (a) and r-value (b) for different layers of AZ31 plate.](image)

![Fig. 6 Compressive stress-strain curves at RT for different direction of AZ31 plate.](image)

![Fig. 7 Compressive stress-strain curves at 473 K for different direction of AZ31 plate.](image)
observed to change to be elliptical. Because of high Lankford values, strain in the thickness direction tends to be lower than that in the direction normal to it. Thus, a minor axis of the elliptical section always corresponds to the thickness direction. The section after compression to 80% of the fracture strain is shown in Fig. 9 for the specimen in the rolling direction. At this stage, the major axis of the elliptical section is 11.93 mm in the width direction of the plates, whereas the minor axis is 10.75 mm in the thickness direction.

In case of compressive deformation in the thickness direction, the cross section remained to be circular. This means that the planar anisotropy is negligibly small compared to the non-planer anisotropy in AZ31 magnesium alloy plates. However, as shown in Fig. 10, the outer shape of cylindrical specimen became barrel-shaped after compressive deformation in the thickness direction. Fig. 10 clearly shows that the degree of barreling is higher for a test piece compressed in the thickness direction than that in the rolling direction. In case of the thickness direction, the sectional diameter at the middle part of the specimen is 11.13 mm, whereas that at the top is 10.58 mm. This fact can be attributed to the difference in proof stress, that is, plastic yielding occurs at lower stress because of lower proof stress of the inner layers than the surface layer of the plates. A case just opposite to this has been reported on Ta metal plates, in which a cylindrical specimen changed to be hour glass-shaped after compressive deformation in the thickness direction. In case of Ta plate, higher yield stress is attained at the middle part of the cylindrical specimen due to the difference in the texture developed at different layers of the plate.

### 3.4 Formability

Deep drawability of the different layers of the plates was evaluated for the blanks of 1 mm thick taken out of three different layers by conical cup tests. The obtained results are shown in Fig. 11. The limiting drawing ratio is lowest for S-layer and inner layers show higher deep drawability than the surface layer of the plates. It is postulated that high severity of the basal plane texture is detrimental to the deep drawability. The stretch formability of different layers of the plates was evaluated by Erichsen tests. The obtained Erichsen values shown in Fig. 12 clearly indicate that the stretch formability is lowest for S-layer and inner layers show higher stretch formability. It should be noticed that these formability values obtained for the blanks from the thick AZ31 plates are higher than those from the sheets of 0.8 mm in thickness. However, these formability values are still
much lower than those of cold rolled steel sheets or commercially pure aluminum sheets.

From the foregoing results of formability tests, the formability of magnesium sheets can be improved by decreasing the severity of the basal plane texture. Poor formability generally observed in magnesium alloy sheets at room temperature can be attributed to the differences in the severity of the basal plane textures.

4. Conclusions

(1) In AZ31-O magnesium alloy plates of 20 mm in thickness, the severity of the basal plane texture is higher at the surface layer than the inner layers. Elongation is lower at the surface layer. The Lankford value (r-value) is higher at the surface layer than the inner layers. Such differences in tensile properties between the surface and inner layers can be attributed to the differences in the severity of the basal plane textures.

(3) In compression tests in different directions of the AZ31 plates at room temperature, yield stress in the rolling and width directions is appreciably lower than proof stress in the thickness direction. An initially cylindrical specimen changed to be barrel-shaped after compressive deformation in the thickness direction of the plates. Such anisotropic and non-uniform deformation behavior was not observed in compression tests at 573 K.

(4) In conical cup and Erichsen tests, blanks taken from inner layers of the AZ31 plates showed higher formability than those from the surface layer in both deep drawing and stretch forming. Formability of magnesium alloy sheets can be improved by decreasing the severity of the basal plane textures.

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REFERENCES