Biaxial Compressive Behavior and Tension-Compression Asymmetry on Plastic Deformation of Cast and Extruded AZ31 Magnesium Alloys

Ichiro SHIMIZU

1 Department of Mechanical Engineering, Okayama University of Science, Okayama 700-0005, Japan

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Abstract: The tension-compression asymmetry under plastic deformation of cast and extruded AZ31 magnesium alloys was investigated. The cast alloy had a rather random texture, while the extruded alloy had a strong texture in which most of grains have an orientation of their basal planes parallel to the direction of extrusion, namely a basal fiber texture. Uniaxial tension test, uniaxial compression test, and equi-biaxial compression test were performed on both alloys. Based on the results obtained, influences of the deformation pattern and the initial texture on the stress-strain relation and the variation of plastic work were discussed. It was found that the activity of the extension twinning strongly influenced on the stress-strain relations under uniaxial deformations, with regard to the relation between the crystallographic preferred orientation and the loading direction. The comparison of the result under the equi-biaxial compression with that under the uniaxial tension revealed the similarity of mechanical responses, even on strongly textured extruded alloy, owing to the geometrical equivalence on deformation of the specimens. On the other hand, there were clear differences on the fracture stresses as well as the fracture morphologies between the equi-biaxial compression and the uniaxial tension, because of the different fracture mode under compression and tension.

Keywords: Plasticity, AZ31 magnesium alloy, Tension-compression asymmetry, Equi-biaxial compression, Stress-strain relation, Deformation twinning

1. Introduction
Since active deformation systems of most magnesium alloys at an ambient temperature are almost limited to basal slip and \{1012\} extension twinning [1], a crystallographic texture develops during metal forming processes such as extrusion and drawing for bars and tubes, and rolling for sheets. The strong texture induces mechanical anisotropy and causes distinctive stress-strain relation with regard to the activation of deformation twinning [2-4]. Tension-compression asymmetry of mechanical properties of textured magnesium alloys is one specific phenomenon, which should be taken into account on designing the machine components. Therefore, in last few decades, researchers have studied the differences of mechanical behaviors under tension and compression of magnesium alloys. Ball et al. [5] performed uniaxial tension and compression tests on various magnesium alloys, and they found that the tension-compression yield asymmetry was observed on extruded alloys having strong texture but not on wrought alloys having random texture. Later, Yin et al. [6] pointed out that the tension-compression yield asymmetry of AZ31 extruded alloy was strongly influenced by the loading direction with respect to the extrusion axis. Besides, tension-compression yield asymmetry has been examined on the influences of strain rate [7], temperature [8], r-value [9], heat-treatment [10], and so on. However, in all the researches, the test methods utilized were limited to uniaxial tension and uniaxial compression. Since the geometrical shape change under the uniaxial tension is different from that under the uniaxial compression, the comparison of mechanical behaviors between both tests includes not only influence of loading direction but also that of geometrical deformation.

In this study, uniaxial tension, uniaxial compression, and equi-biaxial compression tests were performed on cast and extruded AZ31 magnesium alloys, because the geometrical deformation under the uniaxial tension is ideally the same with that under the equi-biaxial compression. First, the stress-strain relations of both alloys were investigated to confirm the influences of the initial texture. Next, the mechanical response under the uniaxial tension was compared with that under the equi-biaxial compression, in order to separately evaluate the influences of loading direction and geometrical deformation on the plastic deformation behavior. It is expected that the results obtained are effective to clarify the primary cause of the tension-compression asymmetry of magnesium alloys, and it is also useful to accuracy improvement for analyses of metal forming processes including biaxial stress state, such as forging and extrusion.

2. Experimental Methods

2.1 Specimens
The commercially available cast and extruded AZ31 magnesium alloys were used. The cast material (2.90 wt% Al, 0.89 wt% Zn) was supplied as a cylindrical rod of 89 mm in diameter, while the extruded material (3.16 wt% Al, 1.13 wt% Zn) was a cylindrical rod of 22.5 mm in diameter. The former was further annealed at 523 K for 2 hour to confirm the random texture. The average grain sizes of the cast and extruded alloys were about 180 μm and 60 μm, respectively. Figure 1 shows \{0001\} and \{1120\} pole figures of both materials obtained by an electron backscatter diffraction method. It is clear that the cast alloy has rather random texture, while the extruded alloy has
is true plastic strain, and subscripts 1 and 2.

Fig. 2. The tensile specimen was machined from the rod parallel to the extruded rod axis.

strong texture in which the basal planes of grains are about parallel to the extruded rod axis.

The shapes and dimensions of specimens were shown in Fig. 2. The tensile specimen was machined from the rod materials with a square cross-section of \(7 \times 7\) mm\(^2\). The cast specimens were taken as the longitudinal direction be parallel to the radial direction \((x-\) and \(y-\)directions) and to the rod axis \((z-\)direction) of the material, while the longitudinal direction of the extruded specimen was taken to be parallel to the rod axis \((z-\)direction) because of small diameter of the extruded rod material. The cube shaped specimen with an edge length of 7 mm was also machined for the uniaxial compression test and the equi-biaxial compression test. All surfaces of specimens were abrasive finished and then applied to the mechanical tests.

2.2 Tensile and compression tests

The uniaxial tensile test was carried out using a Shimadzu universal testing machine at a crosshead speed of 5 mm/min.

The uniaxial and equi-biaxial compression tests were performed by using the lab-made compression test machine [11] at an average strain rate of \(5 \times 10^{-4}/\)s. In compression tests, the die/specimen interfaces were lubricated by boron nitride mixed with silicone grease to reduce friction. All the tests were conducted at room temperature. The stress-strain relation in the uniaxial tension is compared with that in the uniaxial compression to reveal the yield asymmetry. Since the geometrical change of specimen in the uniaxial tension is ideally equivalent to that in the equi-biaxial compression, when the compressions were performed simultaneously in \(x-\)and \(y-\)directions, the results of both tests were compared to evaluate the influence of geometrical deformation on the plastic deformation behavior of AZ31 magnesium alloys.

The true stress \(\sigma\) and the true strain \(\epsilon\) were calculated by load and displacement under the assumption of volume constancy. The plastic work \(W\) was then calculated by

\[
W = \int \sigma_i d\varepsilon_i^p + \int \sigma_2 d\varepsilon_2^p
\]

where \(\varepsilon^p\) is true plastic strain, and subscripts 1 and 2 denote two compressive directions perpendicular each other.

3. Results and Discussion

3.1 Stress-strain relation in uniaxial tests

Figure 3 shows true-stress strain relations under the uniaxial tension and the uniaxial compression of cast and extruded AZ31 magnesium alloys.
extruded AZ31 magnesium alloys. The good agreement of stress-strain curves of the cast alloy in uniaxial compressions along three perpendicular directions denotes the mechanical isotropy based on the random texture (Fig. 1(a)). The deviation of the stress-strain curve in the uniaxial compression in z-direction from those in x- and y-directions of the extruded alloy is due to the strong texture (Fig. 1(b)). The "sigmoid" type stress-strain curve in z-compression is known to be related to the activation of twinning, especially in the range of strain having the increasing work hardening rate [3].

It is seen that the tensile stress-strain relation of the cast alloy is only a little larger than the compressive one, so that the tension-compression asymmetry is weak. On the other hand, the compressive 0.2% proof stress (54-58 MPa) of the extruded alloy, that is about one-third smaller than the tensile one (170 MPa), indicates the strong yield asymmetry. It is interesting that the 0.2% proof stress becomes smaller than that of the tensile one, not only in z-compression but also in x- and y-compressions. In z-compression, the specimen stretches both in x- and y-directions, so the extension twinning is easily activated. In x-compression, however, the extension twinning is activated with the elongation in y-direction but not with that in z-direction, because of the texture, in which c-axes ([0001] axes) are perpendicular to the rod axis and are radially distributed. The condition is about the same also in y-compression. This fact implies that the rate of the activated extension twinning in x- and y-compressions is roughly a half of that in z-direction.

The compressive stress in z-compression steeply increases after the compressive strain exceeds 0.1. This phenomenon is explained by Barnett [12] as that the basal slip becomes easy in the twinned region due to the reorientation by the extension twinning, together with the additional hardening by the dislocation interactions with twin boundaries. In that case, the twinned region is ideally oriented (86° around <1210>) so as the c-axis is near to parallel to the direction of greatest contraction (z-direction). In x-compression, the same mechanism must arise with the elongation in y-direction. However, after the reorientation, the basal slip can be moved in the favorable direction of less dislocation interactions. This is probably the reason why the strain hardening rate continues to decrease in x- and y-compressions of the plastically anisotropic extruded alloy.

The cross mark at the end of the curve denotes fracture. The compressive fracture strain of the cast alloy is about twice larger than the tensile one. Meanwhile, the compressive fracture strain of the extruded alloy is close to the tensile one. The reason of the difference in the fracture strain between two alloys is not yet clear. However, Ando et al. [13] pointed out that {1011} – {1012} double twinning causes the localization of basal dislocation slip within the twin and may lead to failure. It means that the fracture of magnesium alloys somewhat relates to the activation of twinning.

### 3.2 Mechanical response in equi-biaxial compression

True stress-strain curves obtained by equi-biaxial compressions are shown on Fig. 4. In the equi-biaxial compression, the compressive load and displacement are individually measured in two directions orthogonal to each other, namely in x- and y-axes directions, so that two stress-strain curves are obtained. The stress-strain curves by uniaxial compressions were also plotted on Fig. 4 for comparison.

The two stress-strain curves in x- and y-directions under the equi-biaxial compression agree well, though the compressive stress is greater than that under the uniaxial compression. The curve of the cast alloy exhibit the strain hardening behavior similar to that by the uniaxial compression. However, the stress-strain curve of the extruded alloy under the equi-biaxial compression is different from that under the uniaxial compression. That is, the apparent yield stress is much (about three times) larger than that of the uniaxial compression, and the almost linear hardening in the intermediate strain range appeared on the uniaxial stress-strain relation is scarcely recognized. Those differences are probably caused by the difference of the extension twinning activity between the equi-biaxial compression and the uniaxial compression. The direction of extension under the equi-biaxial compression is much more restricted than that under the uniaxial compression, so that the ratio of grains, in which extension twinning is activated, can be less.

![Equi-biaxial Compression](image)

Fig. 4 True stress-strain relations in uniaxial compression and equi-biaxial compression of AZ31 magnesium alloys
3.3 Comparison of mechanical responses under equi-biaxial compression and uniaxial tension

When a yield locus of the material is obvious, the mechanical responses under the different deformation patterns can be compared by means of an equivalent stress-strain relation. However, the yield criterion for the plastically anisotropic magnesium alloy has not yet been clarified to the large strain range. Therefore, the plastic work is employed here to compare the mechanical responses between the equi-biaxial compression and the uniaxial tension. Figure 5 shows the flow stress-plastic work relations of the cast and extruded alloys. It is clearly seen that the flow stress under the equi-biaxial compression is very similar to that under the uniaxial tension, when it is plotted against the plastic work.

Figure 6 shows the equi-plastic work points of uniaxial tension, uniaxial compression, and equi-biaxial compression plotted on the stress space at the plastic work $W = 5$ MJ/m$^3$ and $W = 20$ MJ/m$^3$. In this figure, the results of three specimens for each test are shown to check the repeatability. The dotted curves indicate the locus by the isotropic von Mises yield function matched to the result of uniaxial tension. In Fig. 6 (a), it is recognized for the cast alloy that the stress point of equi-biaxial compression is just on the same locus with that of the uniaxial tension, both at $W = 5$ MJ/m$^3$ and 20 MJ/m$^3$. This fact implies rather isotropic stress evolution against the plastic work, under the equi-biaxial compression and under the uniaxial tension. The same tendency is also seen on the anisotropic extruded alloy in Fig. 6 (b), though the stress under the uniaxial compression is much lower than those of the uniaxial tension and the equi-biaxial compression.

Figure 7 shows the crystal orientation in surface normal direction of the cast AZ31 magnesium alloys at plastic work of 6 MJ/m$^3$ under equi-biaxial compression and uniaxial tension. On both maps, the extension twins are clearly observed within several grains. Since the cast alloy had a rather random texture, there were some grains in which twins were not activated. The twin area fraction were then evaluated quantitatively as 11.0 % for the equi-biaxial compression while 10.1 % for the uniaxial tension. The nearly equivalent values of the twin area fraction under the equi-biaxial compression and the uniaxial tension support the similarity of mechanical response.

![Fig. 5 Comparison of true stress-plastic work relations between uniaxial tension and equi-biaxial compression of AZ31 magnesium alloys](image)

![Fig. 6 Equi-plastic work plots of stresses under uniaxial tension, uniaxial compression, and equi-biaxial compression of AZ31 magnesium alloys](image)
shown in Fig. 6.

From the results above, it can be concluded that the mechanical response of AZ31 magnesium alloy under the equi-biaxial compression is about the same with that under the uniaxial tension, regardless of the plastic anisotropy induced by the texture. It is because the deformation of specimen under the equi-biaxial compression is geometrically equivalent with that under the uniaxial tension. Since the activations of slip and twin systems are strongly influenced by the relation between the crystallographic orientation and the loading direction on the grain, there may be less influence of the sign of the stress, tensile or compressive. On the other hand, the mechanical response under the uniaxial loading is strongly affected by the plastic anisotropy. On the material having strong texture, the stress-strain behavior under the uniaxial compression is markedly different from that under the uniaxial tension. It is so called tension-compression yield asymmetry investigated by many researchers.

3.4 Fractured shapes by uniaxial tension and equi-biaxial compression

Although the mechanical response under the equi-biaxial compression is similar to that under the uniaxial tension, there is clear difference between the compressive fracture and the tensile fracture of AZ31 magnesium alloys. The stress values at fracture are plotted in Fig. 6. It is obvious that the fracture stress is much more improved under the equi-biaxial compression than that under the uniaxial tension, not only on the isotropic cast alloy but also on the anisotropic extruded alloy. Such improvement is, in macroscopic point of view, due to the different fracture mode. Figures 8 and 9 show the fractured specimens under the equi-biaxial compression and under the uniaxial tension, respectively. It is clearly seen that the fracture is governed by shear mode under the equi-biaxial compression, but the fracture under the uniaxial tension is ductile mode, probably based on void nucleation accompanied with a certain extent of uniform elongation. The difference of the fracture mode under the equi-biaxial compression from that under the uniaxial tension may support the improved fracture stress and thus induces "fracture asymmetry" of AZ31 magnesium alloys.

4. Conclusions

The tension-compression asymmetry on plastic deformation behavior of AZ31 magnesium alloy has been investigated, by means of uniaxial tension, uniaxial
compression, and equi-biaxial compression. Two types of magnesium alloys, cast alloy having random texture and extruded alloy having strong texture, were employed and the influence of initial texture on the mechanical response was studied.

The comparison of stress-strain relations under uniaxial tension and compression revealed the strong influence of extension twinning on the strain hardening. The activation of the extension twinning induced lower proof stress and sigmoid type hardening phenomenon under the compression in the rod axis direction of the extruded alloy, namely tension-compression yield asymmetry.

It was clearly shown that the flow stress under the equi-biaxial compression was about the same with that under the uniaxial tension, when it was plotted against the plastic work. This fact leads us to conclude that the mechanical response of AZ31 magnesium alloys under the equi-biaxial compression is about the same with that under the uniaxial tension, because of the geometrically equivalent deformation.

Although the mechanical response was similar to each other, the fracture stress under the equi-biaxial compression was much improved from that under the uniaxial tension, that is, fracture asymmetry. The improved ductility under the equi-biaxial compression is due to the shear dominant fracture and probably to the negative large value of the hydrostatic stress.

Nomenclature

- \( W \): plastic work [MJ/m\(^3\)]
- \( \varepsilon \): true strain
- \( \sigma \): true stress [MPa]

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References


