Deformation Behavior and Texture Formation in AZ80 Magnesium Alloy during Uniaxial Compression Deformation at High Temperatures*

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High temperature uniaxial compression deformation is conducted on AZ80 magnesium alloy at 673 and 723 K by varying the strain rates ranging from 1.0 × 10⁻⁴ to 5.0 × 10⁻² s⁻¹ in order to investigate the behaviors of deformation and texture formation. Particular attention is paid to the development of basal texture. Under the deformation conditions of this study, work softening is observed in all the stress–strain curves without exception. The results of the microstructure observation reveal occurrence of dynamic recrystallization. Formation of fiber texture during the deformation is confirmed. The main component is (0001) when the peak stresses appearing in the stress–strain curves are more than 15–20 MPa, and it develops together with an increase in the peak stress. In contrast, weak fiber textures having a main component at a position 29° away from the basal plane are formed with deformation conditions giving peak stresses of less than 15 MPa. The stress exponent changes at a peak stress near 20 MPa, suggesting that change in the texture corresponds to the change in the deformation mechanism. It is concluded that the formation of basal texture is due to the continuous dynamic recrystallization resulting from the growth of the subgrains formed by the deformation. [doi:10.2320/matertrans.H-M2012832]

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1. Introduction

Magnesium alloys have been attracting attention as lightweight structural materials, and an expansion of their application in various fields such as the automobile industry is expected. However, their use is still limited because of the poor ductility caused by insufficient number of independent slip systems.

Magnesium alloys with poor workability at room temperature show increased ductility at elevated temperatures due to the non-basal slip activities. Thus magnesium alloy plates can be produced by plastic working. When plates are manufactured by hot rolling, basal texture is frequently developed.1) When the basal plane aligns parallel to the plate surface, subsequent plastic working is difficult. Hence, research on texture randomization has also been conducted.2) Although several studies have been carried out on the formation mechanism of basal texture by hot rolling, the mechanism has not been clarified enough.3)

Two of the authors studied the formation behavior of textures in AZ31 and AZ61 magnesium alloys under high temperature uniaxial compression deformation and found that the degree of texture development and the main component changed during dynamic recrystallization with the deformation conditions.4) This means that the texture can be controlled by changing the conditions of hot working.

Texture control is considered to be more important for the high-strength AZ80 alloy, which has a higher solute concentration than AZ31 and AZ61, but there seem no studies that examine the texture formation behavior during hot working of this alloy. Accordingly, in this study, uniaxial compression deformation of AZ80 was carried out at high temperatures under various conditions. Behaviors of the microstructure and texture evolution are studied and their formation mechanisms are discussed.

2. Experimental Procedure

Table 1 shows the results of the chemical analysis of AZ80 used in this study. Concentration of the main alloying element Al is slightly less than 8% by mass. A 60 mm × 60 mm × 40 mm rectangular plate was cut by machining an ingot of AZ80, and rolling was carried out at 673 K with a rolling reduction of 30%. Uniaxial compression test specimens of 12 mm diameter and 18 mm height were prepared by machining from the rolled plate in such a way that the rolling plane was parallel to the compression plane, and tests were carried out after annealing at 723 K for 1 h. The grain size of the sample after annealing was 42 μm.

Uniaxial compression tests were carried out at two temperatures, 673 and 723 K, and in the strain rate range of 1.0 × 10⁻⁴–5.0 × 10⁻² s⁻¹. In order to prevent change in the microstructure after the tests, the samples were quenched in oil immediately after the deformation. After preparing the mid-plane section of the specimen by polishing, the surface was finished using an Emery paper and a silica particle (0.04 μm) suspension, followed by microtexture observation and texture measurement. The texture measurements were carried out by the Schulz reflection method using Cu Kα radiation. The five pole figures of [1010], [0001], [1011], [1012] and [1120] were measured. Based on the five pole figures, the crystal orientation distribution function (ODF) was determined by the Dahms and Bunge method.5) Main component and degree of development of the textures

Table 1 Chemical composition of AZ80 magnesium alloy (mass%).

<table>
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<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
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<td>7.98</td>
<td>0.46</td>
<td>0.16</td>
<td>0.014</td>
<td>0.0012</td>
<td>Bal.</td>
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were determined by drawing the inverse pole figures based on the ODF. In addition to the X-ray measurements, Electron Back-Scattered Diffraction (EBSD) measurements were also performed. EBSD measurements were carried out after electrolytic polishing.

Figure 1(a) is the (0001) pole figure that shows crystal orientation distribution of the sample before the compression test. Pole densities are projected onto the compression plane. Mean pole density is used as a unit. High density is observed at the center of the pole figure. Figure 1(b) is the inverse pole figure showing the density distribution of the compression axis. The mean axis density is used as a unit. At the bottom of the figure, value of the maximum axis density and its position is expressed as (α, β). α is the angle between (0001) and the position of maximum axis density, while β is the rotation angle around [0001] from the [0001]-[1010] line to the position of the maximum axis density. β = 0° means that the maximum axis density exists on the [0001]-[1010] line, while β = 30° indicates that it is on the [0001]-[1120] line. (0, 0) signifies that [0001] is the position of the maximum axis density, where the basal texture is being formed. In Fig. 1(b), the axis density is a maximum on [0001], which is 4.8 times the mean axis density, indicating the presence of a weak basal texture before the compression test.

3. Experimental Results

3.1 Behavior of deformation

Figure 2 is an example of the stress–strain curve for the deformation at 673 K. All the stress–strain curves show that the maximum stress (hereafter referred to as the peak stress) appears in the initial stage of the deformation, that is, all are work softening type curves. Both peak stress and flow stress increase with increasing strain rate. Work softening type stress–strain curves were observed in all the cases in this study. Although the results are not shown here, when the temperature is changed to 723 K, the flow stresses for the same strain rate decrease without exception. Figure 3 is the result of the microstructure observation by EBSD on the longitudinal cross-section of a specimen deformed at 723 K up to the strain of −1.0, under the strain rate of 5.0 × 10^{-3} s^{-1}.

Vertical direction in the figure is the direction of compression. The crystal orientation of the compression plane is given by the color shown in the standard triangle. An almost equiaxed crystal grain structure is constructed.
Despite the deformation up to a true strain of $-1.0$, in this case, the grain size evaluated on the compression plane is 90 $\mu$m, which is slightly more than twice the grain size of 42 $\mu$m before the deformation. The occurrence of recrystallization during the deformation is thus confirmed. Figure 4 shows the relationship between the grain size after the deformation and the peak stress evaluated from stress–strain curves. Changes in the grain size caused by the deformation at the two temperatures can be expressed as a function of the peak stress, which shows that the grain size decreases with an increase in flow stress.

3.2 Texture

Figure 5 is the $\{10\bar{1}1\}$ pole figure for the specimen deformed at 723 K up to a true strain of $-1.0$ under the strain rate of $5.0 \times 10^{-3} \text{s}^{-1}$. Pole densities are projected onto the compression plane. The average pole density is used as a unit. The pole density distribution is concentric, confirming the formation of a fiber texture. Changes in the pole density caused by the deformation at the two temperatures can be expressed as a function of the peak stress, which shows that the grain size decreases with an increase in flow stress.

4. Discussion

4.1 Deformation mechanism

Figure 7 is a double logarithmic plot showing the stress–strain rate relationship at the strain of $-0.5$. At either of the temperatures (673 and 723 K), the relationship can be approximated by two straight lines. The slope of the line, so-called stress exponent $n$, changes from 3.7 and 3.3 on the lower stress side to 5.7 and 5.8 on the higher stress side at the two temperatures, respectively, and thus has similar values regardless of the temperature. The change occurs roughly in the range of 20–30 MPa.

Various studies have been conducted on the relationship between the stress exponent and the high temperature deformation mechanism, and it is thought that when the
value of $n$ is around 3 in solid solution alloys, the motion of dislocations dragging the solute atom atmosphere becomes predominant mechanism for the deformation. When the value of $n$ is 5, the primary deformation mechanism is considered to be free-flight dislocation motion.\(^7\,^8\) In the case of AZ80 examined in this study, the grain size changes due to deformation as shown in an example in Fig. 3. The grain size has a one-to-one correspondence with the peak stress as shown in Fig. 4. These facts indicate the occurrence of dynamic recrystallization during the high temperature deformation of this alloy. Other researchers have also reported the occurrence of dynamic recrystallization in AZ alloys\(^9\,\,^10\).

Above study on the $n$ value was made for the deformation at the steady state creep region which appeared in the tensile creep test. The starting strain for the steady state creep deformation was small in comparison with the present case and dynamic recrystallization was not found in the tensile creep tests. Therefore, it cannot be clearly concluded that the change in $n$ value seen in Fig. 7 signifies a change in the deformation mechanism. However, two of the authors found that an Al–Mg alloy which is known to show a typical alloy type deformation behavior also generates dynamic recrystallization by the deformation up to a large amount of strain at high temperatures. It was found that the $n$ value during dynamic recrystallization was nearly 3, which matched the $n$ value at the tensile creep test of the amount of strain in the range wherein dynamic recrystallization was not observed.\(^11\) From these facts, it was concluded that the change in the $n$ value seen in Fig. 7 may be due to change in the mechanism that controls the dislocation motion.

### 4.2 Formation mechanism of basal texture

In the previous sections, it was made clear that when an AZ80 alloy was deformed in the uniaxial compression mode at high temperatures, (1) a fiber texture is formed, (2) the main component of the fiber texture changes with the deformation conditions, (3) the value of $n$ with a boundary of around 20–30 MPa stress, is around 5 for the high stress side and around 3 for the low stress side, which signifies a change in the deformation mechanism, and (4) dynamic recrystallization occurs. Based on these facts, the formation mechanism of basal texture is discussed in this section.

Figure 8 shows relationship between the position of the main component of the texture, levels of texture, that is, the maximum axis density value in the inverse pole figure, and the peak stress. The results for the two temperatures are shown together. It is seen that the maximum value of the axis density appears at a position 29° away from (0001) for peak stresses of less than 15 MPa, whereas it appears at (0, 0) when the peak stress is above 15–20 MPa. The latter means that the basal component becomes the main component of the texture. The maximum values of the axis density at peak stresses of less than 15 MPa are at the most about 5 times the mean axis density. At peak stresses of more than 20 MPa, however, the values increase monotonically with the increase in peak stress, and a sharp basal texture, with 15 times the mean axis density, is formed at the maximum.

Figures 9(a) and 9(b) show the EBSD observation at the longitudinal section of the specimens after the deformation up to −1.0 in true strain at two deformation conditions wherein the main component of the texture and the maximum axis density differ. The vertical direction is the compression direction. (a) and (b) are the microstructures corresponding to the deformation giving peak stresses of 47 and 8 MPa in Fig. 8, respectively. Sharp basal texture is formed in (a) while the maximum axis density exists at (29, 0) in (b). The colors in the figure indicate crystal orientation of the compression plane. Both the samples underwent deformation up to a true strain of −1.0, but there was no significant change in grain size along the compression direction. This indicates occurrence of grain boundary migration. The grain size changes depending on the deformation condition, as already shown in Fig. 4. A microstructure at the longitudinal cross section of the specimen with basal texture weaker than Fig. 9(a) is already shown in Fig. 3. It can be seen from Fig. 3, Figs. 9(a) and 9(b) that the basal texture develops as the grain size becomes smaller.
Two of the authors examined the process of formation of texture in Al–Mg solid solution alloys under high-temperature uniaxial compression deformation, and found that the [011] fiber texture which developed early in the deformation, changed gradually into a [001] fiber texture with increasing strain above $-1.0$ in true strain. It was considered that the grain boundary migration progresses with increasing strain, and that the [011] oriented crystal grains which are stable against uniaxial compression of FCC crystal and formed initially in the deformation, are consumed. Thus, the [001] fiber texture develops.

It is concluded that the [001] texture develops by grain boundary migration because of the following characteristics of this orientation and the effect of solute atoms. Namely, (1) [001] is an orientation with a small Taylor factor and hence low stored energy, (2) the crystal orientation dependence of the stored energy increases at the deformation condition wherein the distribution of the dislocation is uniform due to the effect of the solute atom atmosphere, (3) thus it becomes easier for the crystal grains with [001] to consume crystal grains with [011] orientation and (4) [001] orientation is also stable against uniaxial compression deformation. In order to verify this concept, size of grains having [001] orientation after the high temperature deformation was examined on the practical alloys AA5182 and AA5052 of the Al–Mg system. It was found that the grains with [001] orientation were larger than the grains with other orientations, which supports the conclusion.\(^{12}\) However, development of the basal texture in AZ80 is entirely different from the evolution of [001] texture in Al–Mg solid solution alloys. That is, the dimensions of grains having [0001] orientation are smaller than grains with other orientations; which suggests that the [0001] texture is not formed by the preferential growth of grains.

Basal slip system and prismatic slip system cannot contribute to the compression deformation along [0001] orientation, but a total of six pyramidal slip systems with equal Schmid factors exist in this orientation. This means that this orientation is stable against high temperature compression deformation. That is, crystal rotation during the high temperature uniaxial compression deformation is unlikely to occur for the [0001] orientation, so the orientation is considered to remain unchanged after the deformation. However, even though the changes in crystal orientation due to the deformation do not occur, the crystal orientation distribution undergoes change if crystal grains of other orientations consume (0001) grains in case of dynamic recrystallization. Thus for the development of basal texture, it is necessary that (0001) is stable against deformation and the grains capable of consuming grains with (0001) orientation are not generated. Figure 9(a) shows that many of the fine grains have orientations close to (0001). This means, the newly generated crystal grains have orientations close to (0001). Therefore, it is considered that weakening of texture during dynamic recrystallization where grains with high dislocation densities are consumed by the newly formed grains does not occur. Jin, et al. reported that the crystal grains with basal orientation were produced by [1012] twinning, and the basal texture was formed by the growth of such grains.\(^3\) However, from the orientation distribution shown in Fig. 1, it is hard to expect frequent twinning during high temperature deformation. In fact, twins are not observed in Fig. 9(a).

Figures 10(a) and 10(b) show the results of the EBSD observation and texture measurement for the specimens deformed at temperatures and strain rates giving the sharpest basal texture. (a) and (b) are deformed at 673 K under a strain rate of $5.0 \times 10^{-2}\text{s}^{-1}$ up to strains of $-0.4$ and $-1.0$ respectively. The color indicates orientation of the compression plane. At a strain of $-0.4$, the grain size is smaller than that in case of the annealed state. At the same time, the accumulation of the axis density towards [0001] is a little over 7 times higher. When the true strain is increased up to $-1.0$, the grain size reduces further and at the same time, accumulation of the axis density towards [0001] becomes as high as 15 times. It has been pointed out that the dynamic recrystallization occurring in magnesium alloys is a continuous type.\(^{10}\) As shown in Fig. 7, the n value at the deformation condition wherein the basal texture develops is around 5. Although there is a remaining problem noted in 4.1 on the relationship of the change in the n value for the high temperature uniaxial compression deformation and the deformation mechanism, assuming that the n value of 5 seen here denotes free flight dislocation motion, the deformation condition for the development of the basal texture is in agreement with the deformation condition for the development of subgrains. It is still unclear which crystal orientation is stable against deformation under the activities of basal and non-basal slip systems. However, the dependence of basal texture development on the deformation condition given in Fig. 8 can be understood by considering the formation of subgrains with crystal orientations near (0001) by deformation and occurrence of continuous dynamic recrystallization. Development of subgrain boundary towards high angle boundary, formation of new grains in twins and the bulging of high angle grain boundaries have been proposed as the mechanisms of continuous dynamic recrystallization. These mechanisms were proposed for pure magnesium\(^{13}\) and a magnesium alloy (AZ31)\(^{14,15}\) but the deformation conditions for the mechanism of development of subgrain boundaries towards high angle boundaries stated in the present study are consistent with those reported earlier.\(^{13-15}\)

4.3 Texture formation in low flow stress conditions

As stated in Section 4.2, if the change in the n value corresponds to the change in the rate controlling mechanism for dislocation motion, and n = 5 corresponds to the free flight motion of dislocations, then formation of the basal texture can be understood to be resulting from continuous dynamic recrystallization. According to the deformation mechanism map, so called solute atom atmosphere dragging is the rate controlling mechanism in the deformation of an Al–Mg alloy, for example, under the condition of high temperature and low strain rate.\(^{16}\)

Unlike the case that free flight motion of dislocation dominates deformation, which is described in 4.2, the development of subgrains is suppressed in this case. In Fig. 9, the misorientation spread between adjacent orientations is shown by a black-lined 15 to 180° high angle grain boundary, and a gray-lined 5 to 15° low angle grain boundary. For the total
Fig. 9 Grain structure observed at the cross sections after the deformation (a) at 673 K up to the strain of 1.0 under the final strain rate of $5.0 \times 10^{-2} \text{ s}^{-1}$ and (b) at 723 K up to the strain of 1.0 under the strain rate of $5.0 \times 10^{-4} \text{ s}^{-1}$. The colors indicate orientation of the compression plane according to the colors given in the standard triangle. Fraction of the low angle grain boundary and high angle grain boundary are given below the maps.

Fig. 10 Grain structure observed at compression plane and corresponding inverse pole figures after the deformation at 673 K under a strain rate of $5.0 \times 10^{-2} \text{ s}^{-1}$ up to a strain of (a) 0.4 and (b) 1.0.
length of crystal grain boundaries with misorientation angles higher than 5°, the total length fractions of the low angle grain boundary and high angle grain boundary are given below the maps. The fraction of the low angle grain boundary is 14% under the condition (a) where the n value is around 5, while it is 6.0% under the condition (b) where the n value is around 3. Subgrain fraction is high under the deformation conditions giving high peak stresses. Characteristics similar to the results on the longitudinal cross section given in Fig. 9 are also seen in the EBSD measurements of the compression plane for the other deformation conditions.

Subgrains are formed by the interactions between the stress fields of dislocations so as to reduce the total self-energy of dislocations. Therefore, it is considered that difference in the stored energy is not high when subgrains are formed, even if the dislocation density varies according to the orientations. On the other hand, when the dislocations move with solute atom atmospheres, the stored energy is not high when subgrains are formed, even if dislocations. Therefore, it is considered that difference in the plane for the other deformation conditions.

The formation behavior of microstructures and textures under high temperature uniaxial compression deformation in high strength AZ80 magnesium alloys, which are expected to be used in a wide range of applications, is examined by varying the deformation conditions. The major conclusions are as follows.

1. Dynamic recrystallization occurs without exception under the deformation conditions of this study. Fiber textures are formed during the deformation.

2. Main component of the fiber texture is (0001) under deformation conditions showing peak stresses of more than 15–20 MPa. That is, basal textures are formed. The basal texture develops with the increase in the flow stress, reaching a maximum of 15 times the mean axis density.

3. At deformation conditions with the peak stress less than 15 MPa, the main component of the fiber texture is located at a position 29° away from (0001), and the maximum axis density is low, that is, 5 times the mean axis density.

4. Formation of the basal texture at a peak stress of more than 20–30 MPa is considered to be due to the continuous dynamic recrystallization.

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REFERENCES