Change in Crystallographic Orientation Distribution during High Temperature Deformation in an Al-Mg-Mn Alloy Sheet Consisting of Coarse- and Fine-Grained Layers

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The change in crystallographic orientation distribution during high temperature deformation for an Al-Mg-Mn alloy sheet consisting of the coarse-grained surface and the fine-grained center layers has been investigated in order to reveal the deformation mechanism. The grain size dependence of the deformation behavior is discussed in the identical deformation condition by using the specially-prepared sheet. The grain structures in the coarse-grained surface layer of the sample deformed at 713 K are elongated in the tensile direction corresponding to the macroscopic elongation to failure. The structures related to the maximum elongation in both of the surface and center layers have preferred orientations of the tensile deformation. Further, the intragranular misorientation, grain boundary misorientation and high strain rate deformation are analyzed in detail.

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1. Introduction

Continuous cyclic bending (CCB)\(^1\)\(^2\)\(^3\) is a straining technique that can produce high strain in the surface layer and low strain in the central part of the metal sheet. The CCB and subsequent annealing make it possible to produce the gradient microstructure with the coarse-grained surface layer and the fine-grained layer in the middle of the sheet of an Al-4.7 mass%Mg-0.7 mass%Mn alloy (A5083).\(^4\)\(^5\) A part of the authors reported that the high temperature deformation and fracture of the sheet consisting of the coarse- and the fine-grained layers was related to the fine-grained superplasticity and the Class I superplasticity.\(^6\)\(^7\) It was not, however, revealed how both of the superplasticity contribute the deformation up to a large elongation. Further, high strain rate deformation at more than \(5.6 \times 10^{-3}\) s\(^{-1}\) has never been studied unless its industrial application is more interesting.

The purpose of the present study is to investigate change in crystallographic orientation distribution during high temperature deformation for the Al-Mg-Mn alloy sheet consisting of the coarse-grained surface and the fine-grained center layers, in order to reveal the deformation mechanism of the specified sheet.

2. Experimental Procedure

The Al-Mg-Mn alloy sheet used was the same as that in the previous study.\(^8\) The sheet was 1.5 mm thick and its chemical composition is listed in Table 1. The as-received sheet had been manufactured by the process of casting, homogenizing at 803 K, hot rolling, cold rolling with a reduction of 75% and a final continuous annealing at 673 K. Workpiece with a 500 mm length, a 20 mm width and a 1.5 mm thickness was subjected to CCB in the same way\(^7\) up to 20 passes. From the CCBent workpiece tensile specimens were machined with a 6 mm length, a 4 mm width and a 1.5 mm thickness of the reduced section, and a 6 mm radius of fillets. After that, the specimens were annealed at 673 K for 3.6 ks in a salt bath to acquire the fine- and the coarse-grained layers. The sample has thickness fraction of 46\(^\%\)\(^7\) for both surface layers with coarse grains, which was called 20P.A previously.\(^2\)\(^7\) Grain sizes were measured by the liner intercept method as about 64 \(\mu\)m and about 8 \(\mu\)m for the coarse- and fine-grained layers, respectively.

Tensile tests were carried out in air in temperatures of 633 K, 713 K and 793 K using an Instron type testing machine at initial strain rates of \(5.6 \times 10^{-4}\) s\(^{-1}\), \(5.6 \times 10^{-3}\) s\(^{-1}\) and \(1.4 \times 10^{-1}\) s\(^{-1}\). The specimens were tested after heating with an infrared furnace at a rate of 0.57 K s\(^{-1}\). Holding time before tensile testing was 1.8 ks so as to stabilize the test temperature. The elongation to failure was measured from the increase in the gauge length of 5 mm. To avoid the drastic change in microstructure, the specimen was quenched into water immediately after finishing the test.

Crystallographic orientation analysis was performed using SEM/EBSP (scanning electron microscopy/electron backscatter diffraction pattern) technique on the coarse- and the fine-grained layers of the deformed specimens up to failure, and besides, those of the specimen quenched from a given temperature of 713 K immediately before the tensile testing. The sample coordinate system is defined by the longitudinal, long transverse and short transverse directions (L, LT and ST) for the sake of avoiding confusion. The longitudinal direction is parallel to the tensile direction, that is, the rolling direction (RD). The notation RD will be used only for representation of preferred orientations. The EBSP analysis was performed on L-LT plane, and the crystallographic directions aligned with RD (or L) will be colored in inverse pole figure (IPF) maps below.

### Table 1 Chemical composition of alloy used in this study in mass%.

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.03</td>
<td>0.04</td>
<td>Tr.</td>
<td>0.65</td>
<td>4.70</td>
<td>0.10</td>
<td>Tr.</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

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3. Results and Discussion

3.1 Stress-strain curves
Nominal stress vs. strain curves for the present sample are shown at 713 K and $1.4 \times 10^{-1}$ s$^{-1}$ in Fig. 1. The curves in both conditions show a maximum in stress at an early stage and gradual decrease with strain at each strain rate or temperature. In Fig. 1(a) the maximum stresses for the curves exhibit a common strain rate dependence of flow stress for high temperature deformation. The maximum elongation to failure of 254% is obtained at $5.6 \times 10^{-3}$ s$^{-1}$. On the other hand, for the high strain rate deformation the flow stress is considerably affected by the temperature while the elongation is almost independent of it (Fig. 1(b)). The elongation of the present specimen seems to be determined by that of the surface coarse-grained layers, as reported previously.\(^7\)

3.2 Strain rate dependence of microstructural change
We investigate here difference in microstructures before and after the deformation at a temperature of 713 K. The temperature was chosen in the interest of the maximum elongation obtained.\(^7\) Figure 2 displays the inverse pole figure (IPF) maps in tensile direction (RD or L) of the surface coarse-grained layers of the samples deformed up to failure at three strain rates. The IPF map for the sample immediately before testing is also represented. The microstructure of this map has a grain size of about 118 µm and is characterized by the wavy grain boundaries (Fig. 2(a)). The grain structure after the deformation is elongated in tensile direction corresponding to the macroscopic elongation to failure at each strain rate. At a low strain rate the elongated grains seem to be extended in LT due to stored strain energy (Fig. 2(b)). The small black areas distributed are non-analyzable points related to the cavities. The map of the sample tested at 713 K and $5.6 \times 10^{-3}$ s$^{-1}$ (Fig. 2(c)), at which the maximum elongation was obtained for the present sheet, is almost colored red and blue. This indicates the formation of preferred orientations of \((001)\)/RD (or L) and \((111)\)/RD (or L). At a high strain rate (Fig. 2(d)), the same preferred orientations also appear. Moreover, a lot of low angle boundaries and intragranular misorientations, which are shown by the thin black lines and the gradation of colors, respectively, are observed inside the elongated grains. These are evidence of deformation by dislocation glide mechanism. Calculating the aspect ratio of the elongated grains after the test, the largest value of 2.5 is derived for the sample deformed at $5.6 \times 10^{-3}$ s$^{-1}$ from mean grain sizes in L and LT directions. If strains are equivalent in LT and ST during the tensile test, the ideal aspect ratio $r_A$ is derived in the assumption of volume conservation as the next equation.

$$r_A = \left(1 + \varepsilon_N\right)^{3/2}$$  \((1)\)

where $\varepsilon_N$ is the nominal strain in L or tensile direction. The $r_A$ value for the sample with the largest practical ratio is 6.66 by using eq. (1). Then, the practical value is only 38% of the ideal one. The percentage means a contribution of the intragranular deformation which left strain inside the grains after the deformation to failure, to the whole given strain. A 62% of the given strain apparently contributes microstructural changes such as dynamic recrystallization and grain growth. Alternatively, the maximum strain stored inside the grains in this deformation condition is 38%, and excess over the maximum strain led to the microstructural changes.

The inverse pole figure (IPF) maps in tensile direction (RD or L) of the center fine-grained layers are shown in Fig. 3 in the same way. On the whole, the fine grained microstructure in center layer remains after deformation at every strain rate. More detail analysis characterizes three samples deformed at different strain rates. The grain structure at the low strain rate (Fig. 3(b)) consists of somewhat elongated grains and shows no formation of the preferred orientation. The contribution fraction of the intragranular deformation is calculated to be 36%. Alternatively the contribution of the grain boundary sliding (GBS) is estimated as 64%. The value is almost consistent with the previous result that the fraction of the GBS, which was calculated from the offset of scratch marker lines pre-inscribed across grain boundaries on the polished sample surface, varied from 65 to 85% in the fine-grained superplasticity of an Al-Zn-Mg alloy.\(^8\) The grains at the middle strain rate (Fig. 3(c)) have a characteristic bamboo-
### Table 1: Grain Size and Elongation

<table>
<thead>
<tr>
<th>Testing Condition</th>
<th>Mean Grain Size</th>
<th>Elongation</th>
<th>Testing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initially</td>
<td>L8.1 × LT9.1 µm²</td>
<td>0%</td>
<td>0s (713K-1.8ks)</td>
</tr>
<tr>
<td>(b) 5.6 × 10⁻⁴s⁻¹</td>
<td>L8.1 × LT9.0 µm²</td>
<td>177%</td>
<td>3868s (64m28s)</td>
</tr>
<tr>
<td>(c) 5.6 × 10⁻³s⁻¹</td>
<td>L12.1 × LT7.0 µm²</td>
<td>254%</td>
<td>530s (8m50s)</td>
</tr>
<tr>
<td>(d) 1.4 × 10⁻¹s⁻¹</td>
<td>L165 × LT87 µm²</td>
<td>174%</td>
<td>15s</td>
</tr>
</tbody>
</table>

### Fig. 2: Inverse Pole Figure Maps in Tensile Direction in the Coarse-Grained Surface Layer
- (a) Immediately before testing
- (b) 5.6 × 10⁻⁴s⁻¹
- (c) 5.6 × 10⁻³s⁻¹
- (d) 1.4 × 10⁻¹s⁻¹

### Fig. 3: Inverse Pole Figure Maps in Tensile Direction in the Fine-Grained Center Layer
- (a) Immediately before testing
- (b) 5.6 × 10⁻⁴s⁻¹
- (c) 5.6 × 10⁻³s⁻¹
- (d) 1.4 × 10⁻¹s⁻¹

**Fig. 2** Inverse pole figure maps in tensile direction in the coarse-grained surface layer: (a) immediately before tensile test, and after deformation to failure at 713 K and various strain rates ((b)–(d)).

**Fig. 3** Inverse pole figure maps in tensile direction in the fine-grained center layer: (a) immediately before tensile test, and after deformation to failure at 713 K and various strain rates ((b)–(d)).
like shape which seems to evolve from deformed structure. The bamboo-like grains possess similar orientations or colors in the figure. Thus, the grain structure was obviously formed with the notable contribution of the intragranular deformation, although that of the GBS was not denied. The equiaxed grains which are slightly smaller than those before testing appear in the microstructure developed at $1.4 \times 10^{-3}$ s$^{-1}$ (Fig. 3(d)). The smaller grains were probably developed by dynamic recrystallization because they have a preferred orientation. The clusters of grains with similar orientations of (001)//RD and (111)//RD are observed in the figure.

3.3 Preferred orientation components

According to Calnan and Clewes, two main components of (001)//RD and (111)//RD are demonstrated as tensile deformation texture in fcc metals. In order to clarify the development of the tensile deformation texture, three main components parallel to RD including the two ones as described above are investigated here.

Figure 4 represents fractions of (001)//RD, (111)//RD and (011)//RD in the surface and center layers. Remarkable increase in the tensile texture components are found in the surface layer after deformation at 713 K, and particularly the higher strain rates. The difference in the development between the two components is observed ambiguously. Analogous tendency is also found for the component of the center layer except for the case of $5.6 \times 10^{-4}$ s$^{-1}$, at which the largest contribution of grain boundary sliding to deformation was expected. The increase in the components was fairly small compared with that in the surface layer since the center layer has the fine grain size.

3.4 Intragranular misorientation

In Section 3.2, a lot of the intragranular misorientations were observed clearly inside the elongated grains, especially in the surface layer. The misorientation reflects the stored strain energy. The most appropriate quantity is “kernel average misorientation (KAM)” to evaluate the stored energy for a given point. The KAM is defined for a given point as the average misorientation of that point with all of its neighbors, which is calculated with the proviso that misorientations exceeding a tolerance value of $5^\circ$ are excluded from averaging calculation. The magnitude of the KAM is affected by the scan step size, which was always set as 1 μm or 10 μm in the present paper.

The KAM distributions in the surface and center layers are indicated before and after testing in Fig. 5. There is a marked difference between both layers. During the deformation the KAM distribution varies drastically in the surface layer while a minor change is found in the center layer. The ratio of the mean KAM at $1.4 \times 10^{-3}$ s$^{-1}$ to that before testing is calculated for the former as $1.20/0.77 = 2.34$ in contrast to the ratio for the latter is calculated as $0.68/1.00 = 0.68$. The strain energy rather lowers during the deformation in the fine-grained center layer. It is obvious that the strain energy is difficult for the fine-grained structure to store during the high temperature deformation.

3.5 Grain boundary character

As the GBS is affected by grain boundary character, to investigate the change in distribution of grain boundary misorientation during the deformation is very interesting. Figure 6 shows the grain boundary misorientation distributions before and after the deformation at 713 K and $5.6 \times 10^{-3}$ s$^{-1}$. The before-testing sample has a common misorientation with a peak around 45 degrees, which is often found for a random texture. After the deformation the fraction of the low angle grain boundaries rises up extraordinarily in the surface layer while the fraction increases considerably. Based on the IPF maps (Figs. 2 and 3), the grain boundary character distributions before and after the deformation were analyzed. The results are summarized in Table 2. The change in grain boundary characteristic distribution in both of the layers is very simple. The random and the coincidence site lattice (CSL) boundaries decreases by 40% in the fraction during deformation in the surface layer in contrast to a large increase by a factor of 10 for the low angle boundaries. No dependence on the initial strain rate is observed. Generally speaking, little change in all the fractions is kept during the deformation in the fine-grained center layer. This tendency is intimately related with the fact that the strain energy is difficult for the fine-grained structure to store during the high temperature deformation. The fine grains can remain during the deformation through grain boundary sliding or dynamic recrystallization.

3.6 High strain rate deformation

As mentioned above, the noticeable phenomena, the formation of low angle boundaries and the dynamic recrystallization were found in both of the layers after the deformation at 713 K and $1.4 \times 10^{-3}$ s$^{-1}$. Then, the microstructures after the deformation at the high strain rate of $1.4 \times 10^{-3}$ s$^{-1}$ are examined.

The IPF maps in tensile direction (RD or L) of the surface and the center layers of the samples deformed up to failure at temperatures of 633 K and 793 K are displayed in Fig. 7. Both of the microstructures in the surface layer are found to have the typical texture of the tensile deformation because they are colored red and blue. While the elongated grains include many low angle boundaries, the evolved band-like grains have the intragranular misorientations, which are developed in L direction compared with LT. The latter may be attributed to dynamic recovery because of the activity of dislocation at a high temperature of 793 K. On the other hand, the finer grains are obtained in the center layer deformed at 633 K and 793 K, which were formed by the dynamic recrystallization. The reason why the grain size after the deformation at 713 K is larger than that at 633 K and 793 K is not found completely. The optimal condition of grain refinement is likely caused at 633 K and 793 K accidentally. The grain boundary character distributions before and after the deformation for the above conditions are listed in Table 3. In the surface layer the same tendency is found as in Table 2. The fraction of the low angle boundaries increase by more than 100% during the deforma-
Mean grain size L127×L77.3μm²
Elongation 168%
Testing time 14s
(a) Surface layer 633K
(b) Center layer 633K

Mean grain size L7.1×L5.6μm²
Elongation 168%
Testing time 14s

Mean grain size L424×L101μm²
Elongation 187%
Testing time 16s
(c) Surface layer 793K
(d) Center layer 793K

Fig. 4 Fractions of primary orientation components in the coarse-grained surface and center layers immediately before tensile testing, and after deformation to failure at 713 K and various strain rates.

Fig. 5 Kernel average misorientation (KAM) distributions in (a) surface and (b) center layers immediately before tensile test, and after deformation to failure at 713 K and various strain rates.

Fig. 7 Inverse pole figure maps in tensile direction in the coarse-grained surface layer after deformation to failure at 1.4 × 10⁻¹ s⁻¹ and (a) 633 K and (b) 713 K in the surface layer, and (c) 633 K and 793 K in the center layer.
4. Conclusions

The change in crystallographic orientation distribution during high temperature deformation for the Al-Mg-Mn alloy sheet consisting of the coarse-grained surface and the fine-grained center layers has been investigated in order to reveal the deformation mechanism of the specially-prepared sheet. The obtained results are summarized as follows:

The grain structures in the coarse-grained surface layer of the sample deformed at 713 K were elongated in the tensile direction corresponding to the macroscopic elongation to failure. The structures related to the maximum elongation in both of the surface and center layers had preferred orientations of the tensile deformation. The characteristic bamboo-like shape of grains was observed in the center layer. It was obvious using the kernel average misorientation (KAM) that the strain energy was difficult for the fine-grained structure to store during the high temperature deformation. The random and the coincidence site lattice (CSL) boundaries decreases by 40% in the fraction during deformation in the surface layer in contrast to a large increase by a factor of 10 for the low angle boundaries. The finer grains of 5.2 µm are obtained by the dynamic recrystallization in the center layer deformed at 793 K.

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REFERENCES


Table 2 Grain boundary character distributions in surface and center layers immediately before tensile test, and after deformation to failure at 713 K and various strain rates. CSL refers to coincidence site lattice boundary.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Character</th>
<th>Before Test</th>
<th>Initial strain rate, s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low angle</td>
<td>4%</td>
<td>42%</td>
</tr>
<tr>
<td>Surface</td>
<td>Random</td>
<td>86%</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>CSL</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Center</td>
<td>Low angle</td>
<td>9%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Random</td>
<td>82%</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>CSL</td>
<td>9%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Table 3 Grain boundary character distributions in surface and center layers after deformation to failure at 1.4 × 10⁻¹ s⁻¹ and various temperatures. CSL refers to coincidence site lattice boundary.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Character</th>
<th>633 K</th>
<th>713 K</th>
<th>793 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Low angle</td>
<td>43%</td>
<td>44%</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>Random</td>
<td>51%</td>
<td>50%</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>CSL</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Center</td>
<td>Low angle</td>
<td>29%</td>
<td>13%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Random</td>
<td>64%</td>
<td>78%</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td>CSL</td>
<td>7%</td>
<td>9%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Fig. 6 Grain boundary misorientation distributions: (a) immediately before tensile test, and after deformation to failure at 713 K and 5.6 × 10⁻³ s⁻¹ in (b) surface and (c) center layers.