Effect of strain and deformation route on grain boundary characteristics and recrystallization behavior of aluminum

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Abstract. The effect of strain and deformation route on the recrystallization behavior of aluminum sheets has been investigated using well lubricated cold rolling and continuous equal channel angular extrusion. Three different deformation routes in plane strain corresponding to (1) simple shear, (2) compression, and (3) the combination of simple shear and compression were performed on 1100 aluminum sheet. Fixed amounts of the equivalent strain of 1.28 and 1.06 were accumulated in each route. In case of the combined deformation route, the ratio of shear strain to the total equivalent strain was varied. The recrystallized grain size was finer if the combined deformation route was employed instead of the monotonic route under the same amount of equivalent strain at either strain level. The density of high angle grain boundaries that act as nucleation sites for recrystallization was higher in materials deformed by the combined route. The orientation imaging micrographs revealed that the change in deformation route is effective for introducing a larger number of new high angle grain boundaries with relatively low misorientation angle.

1. Introduction

It has been reported that the introduction of shear strain during the rolling of sheet materials promotes the refinement of recrystallized grains. A layer of extremely fine recrystallized grains appears beneath the surface of sheets that are hot rolled under high friction conditions [1-3]. In the accumulative roll-bonding process (ARB), rolling without lubrication accelerates grain refinement and strengthening [4,5]. Additional rolling after equal channel angular extrusion (ECAE) also enhances the grain refinement [6-8]. The promotion of grain refinement by a shear strain combined with compressive strain can be, in part, obviously attributed to the increase in equivalent strain. However, it has not been completely understood if the increased grain refinement is totally due to the increase in the amount of equivalent strain or, partly, to the change in strain path. The effect of the shear strain can probably not only be ascribed to the increase in the amount of equivalent strain. It should be considered that this additional strain activates slip systems others than those required by compressive deformation. The activation of multiple slip systems results in a complex deformation microstructure, which includes a large number of nucleation sites that may lead to finer recrystallized grains. The authors have revealed that the combination of compression and shear deformation is effective for grain refinement under a...
fixed amount of strain [9]. However, the effect of the deformation route on the deformation microstructure has not been observed in detail.

In the present study, the effects of the amount of equivalent strain and deformation route on the recrystallization behavior and grain boundary characteristics of 1100 aluminum sheets are investigated by introducing a fixed amount of equivalent strain along three different strain paths, namely simple shear only, compression only, and a combination of simple shear and compression. The ratio of the shear strain to the compressive strain was varied in the combined deformation route.

2. Experimental

Three deformation routes under plane strain condition, specifically (1) simple shear only, (2) compression only, and (3) combination of simple shear and compression, were employed to aluminum 1100-O sheets of commercial purity. Sheets being 2.0 mm thick, 19 mm wide, and 2 m long were processed by conventional rolling and/or conshearing at room temperature. A fixed amount of the equivalent (von Mises) strain was introduced in either path. Two levels of equivalent strain were introduced, namely $\epsilon_{eq}=1.28$ and $\epsilon_{eq}=1.06$. Experimental details of each strain path are described below.

The simple shear was introduced by continuous ECAE of the sheet materials, using the conshearing process [10,11]. The die angle $\theta$ for ECAE was 65°. In order to impose the shear deformation uniformly and cumulatively, not only the strip was turned upside down, but also the extruding direction was reversed after each pass. Conshearing was carried out up to eight passes to obtain the equivalent strain of 1.28. The mean inclination angle of the grains with respect to the rolling direction at mid-plane $\alpha'$ was determined from micrographs. The imposed shear strain $\gamma$ and the equivalent strain $\epsilon_{eq}$ were estimated by the following equations:

$$\gamma = \tan(90° - \alpha')$$  \hspace{1cm} (1)

and

$$\epsilon_{eq} = \frac{1}{\sqrt{3}} \gamma.$$  \hspace{1cm} (2)

The amount of shear strain was varied by varying the pass number of conshearing.

Plane strain compression was introduced by conventional cold rolling with good lubrication. The sheets were rolled with $\phi=130$ mm rolls at a roll peripheral speed of 2 m/min. The equivalent strain was calculated by the following equation:

$$\epsilon_{eq} = -\frac{2}{\sqrt{3}} \ln(1-r).$$  \hspace{1cm} (3)

| notation | equivalent strain | deformation route | strain | shear strain ratio |
|----------|------------------|------------------|-------|-------------------|
| s1(1.28) | 1.28             | simple shear only | $\gamma=2.21$ | 1.00 |
| s0.8(1.28)| 1.28             | simple shear + compression | $\gamma=1.82$, $r=17.3\%$ | 0.83 |
| s0.6(1.28)| 1.28             | simple shear + compression | $\gamma=1.42$, $r=32.9\%$ | 0.64 |
| s0.3(1.28)| 1.28             | simple shear + compression | $\gamma=0.66$, $r=54.1\%$ | 0.30 |
| s0(1.28)  | 1.28             | compression only  | $r=67.0\%$ | 0.00 |
| s1(1.06)  | 1.06             | simple shear only | $\gamma=1.82$ | 1.00 |
| s0.8(1.06)| 1.06             | simple shear + compression | $\gamma=1.42$, $r=18.8\%$ | 0.77 |
| s0.4(1.06)| 1.06             | simple shear + compression | $\gamma=0.66$, $r=44.5\%$ | 0.36 |
| s0(1.06)  | 1.06             | compression only  | $r=60.1\%$ | 0.00 |
in which \( r \) is the reduction in thickness, defined as:
\[
r = \frac{\Delta h}{h_0},
\]
where \( \Delta h \) is the change in thickness induced by rolling and \( h_0 \) is thickness before rolling.

The combined strain was introduced by conshearing, followed by conventional rolling. The equivalent strain of the combined path was calculated as follows:
\[
\varepsilon_{eq} = \frac{1}{\sqrt{3}} \gamma - \frac{2}{\sqrt{3}} \ln(1 - r).
\]

The pass number of conshearing and the reduction in thickness by rolling were varied to obtain a fixed total amount of equivalent strain with various ratios of shear strain to the total equivalent strain. The different deformation routes conducted in the present study are listed in Table 1.

The sheets processed by the nine different routes were annealed at temperatures in the range of 423 K - 673 K for 1.2 ks in oil or salt bath. The Vickers hardness was measured on the longitudinal section of as-processed and annealed specimens. The mean intercept length of the recrystallized grains was taken as grain size. Field emission scanning electron microscope (FE-SEM) equipped with electron backscatter diffraction (EBSD) system was used to obtain orientation imaging micrographs (OIMs).

3. Results

The effect of the shear strain ratio on the softening behavior of the specimens deformed to the equivalent strain of 1.28 is shown in Figure 1. Among the as-processed materials, the rolled specimen s0(1.28) and s0.3(1.28) show higher hardness than the simply sheared sample s1(1.28) and s0.8(1.28). The sharp decrease in hardness caused by the recrystallization is found in all five specimens. The simply sheared specimen shows the highest recrystallization temperature.

The effect of the ratio of shear strain to the total equivalent strain on the recrystallized grain size is

![Figure 1. Effect of deformation route on softening behavior during annealing.](image-url)
clearly shown in Figure 2 for the total equivalent strain of 1.28. The grain size depends on the ratio of the shear strain to the total equivalent strain at all annealing temperatures tested. Near the strain ratio of 0.6, the finest grain size was obtained. Corresponding to the hardness of the as-processed specimens, the simply sheared sample shows the largest grain size. The second largest grain size is observed in the rolled specimen s0(1.28). A monotonic deformation is less effective for grain refinement than the combined deformation route. This suggests that the combination of nearly equal shear and compressive strain is most effective for grain refinement. The grain size increases almost linearly with the increase in annealing temperature. It should be noted that these results are obtained by discontinuous static recrystallization because the applied strain is insufficient to induce continuous recrystallization that often occurs in severely deformed materials. Figure 3 shows the effect of the total equivalent strain on the recrystallized grain size. The grain size decreases with increasing equivalent...
strain. The combined deformation route is more effective for grain refinement, regardless of the amount of total strain.

4. Discussion
In the present study, the effect of the deformation route on the recrystallization behavior has been clarified by varying the ratio of shear strain to compressive strain under the condition of a constant total equivalent strain. The combined deformation route corresponding to a change in strain path promotes grain refinement. In order to discuss the mechanism, OIMs of the as-processed specimens were taken by FE-SEM equipped with an EBSD system. The OIMs of the as-processed materials are shown in Figure 4. The solid lines of the micrographs show boundaries with a misorientation angle larger than 15°, i.e., high angle grain boundaries (HAGBs). In the material that has been subjected to simple shear (s1(1.28)), lamellar blocks surrounded by HAGBs are elongated in an inclined direction. The material after compression (s0(1.28)) has a lamellar structure elongated in the rolling direction (RD), but these grains are thinner than the sheared grains in the s1(1.28) specimen. Likewise, the materials resulting from the application of the combined deformation path (s0.8(1.28), s0.6(1.28), s0.3(1.28)) also have a lamellar structure of elongated grains. However, the density of HAGBs is higher and the grain size is smaller than in case of the materials processed by monotonic deformation. The HAGBs are likely to be formed by grain subdivision [12] due to the change in stable end orientations. The number of nucleation sites for recrystallization is larger in the material that is subject to the combined deformation path. The change in strain path may increase the stored energy and the density of HAGBs, thereby resulting in finer recrystallized grains.

Figure 5 shows the effect of the change in deformation route on the deformation microstructure. The specimens s1(1.28) and s0.8(1.28) are compared. The sample s1(1.28) was obtained by 8-pass ECAE, whereas s0.8(1.28) was obtained by 17% rolling after 6-pass ECAE. The same equivalent strain of 1.28 was introduced to each specimen. In comparison with the 6-pass ECAE processed specimen (s1(1.06)), the distance between high angle grain boundaries decreased by additional 2-pass ECAE in s1(1.28). The colors of the grains remain unchanged, implying that the grains reached stable end orientation already after simple shear at the equivalent strain of 1.06. However, by additional 17% rolling to 6-pass ECAE, the density of HAGBs slightly increases in the s0.8(1.28) specimen and the

![Figure 5. Effect of the mode of additional strain after monotonic shear deformation on the arrangement of high angle grain boundaries and grain orientations.](image)
colors change more frequently than in s1(1.28), suggesting that the grain orientation changes more frequently in the specimen deformed by combined strain. The grains with stable end orientation after simple shear are rearranged by additional compression. Changing the deformation route clearly influences the deformation microstructure, grain orientation, and subsequent recrystallization behavior.

The effect of the ratio of shear strain to the total strain on the density of HAGBs of the specimens deformed to the equivalent strain of 1.28 is shown in Figure 6. The density of HAGBs was obtained by counting the number of intersections of a line of unit length with HAGBs [13]. In case of the specimen s0.6, the density of HAGBs is highest among the five investigated materials, corresponding to the finest recrystallized grain size. The HAGBs are grouped into three classes according to their misorientation angle. The density of HAGBs with misorientation angle higher than 40°, between 30° and 40°, and below 30° are shown in Figure 6. The density of HAGBs with misorientation angle smaller than 40° is higher if employing the combined deformation route, while that of HAGBs with misorientation angle being larger than 40° gradually decreases with increasing the ratio of shear strain. This suggests that the change in the deformation route promotes the increase of HAGBs with relatively low misorientation angle. HAGBs with misorientation angle of more than 40° seem to be difficult to be formed by grain subdivision. Figure 7 shows the effect of the total equivalent strain on the density of HAGBs in dependence of the fraction of shear strain. The effect of the shear strain fraction on the HAGBs density is more prominent in case of large strain deformation.

The change in deformation route may also affect the formation and arrangement of deformation bands. It is expected that more deformation bands would be formed by employing the combined deformation route. However, statistics of deformation bands were not analyzed in detail in the present study.

5. Summary
The dependency of the recrystallization behavior on the deformation route has been investigated under plane strain condition for 1100 aluminum sheets. Equivalent strain of either $\varepsilon_{eq} = 1.28$ or $\varepsilon_{eq} = 1.06$ was applied to the material along the three different strain paths (1) simple shear, (2) compression, and (3) the combination of simple shear and compression. The results are summarized as follows:
(1) The recrystallized grain size after combined deformation is smaller than in case of simple shear or compression, regardless of the total amount of equivalent strain.
(2) The finest recrystallized grain size was obtained at the ratio of 0.6 of the shear strain to the total equivalent strain, regardless of the total amount of equivalent strain.
(3) The grain refinement resulting from the combined deformation route is attributed to the increase in HAGBs.
(4) The change in deformation route promotes the increase of HAGBs with relatively low misorientation angle.

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