Strain hardening and softening in ultrafine grained Al fabricated by ARB process

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Abstract. Deformation behavior of a commercial purity aluminium (99% purity) highly deformed by the accumulative roll-bonding (ARB) process was investigated by analyzing the change in the specimen shape during tensile test precisely. True stress obtained by the specimen shape analysis of the conventionally coarse grained material was found to increase continuously even after necking, which indicated that the necking region was work-hardened. On the other hand, true stress of the ARB-processed Al which showed lamellar boundary structure having the mean lamellar spacing of 220 nm decreased after necking, which was quite different from the result of the coarse grained material. This result suggests that the necking region is not hardened but softened by deformation. The softening is considered to be caused by dynamic recovery at grain boundaries.

1. Introduction

Ultrafine grained (UFG) materials fabricated by severe plastic deformation (SPD) processes [1-3] are known to exhibit excellent mechanical properties and unusual deformation behavior [1, 4, 5]. For example, UFG metals fabricated by ARB process have the elongated lamellar UFG structure and show high strength, which is 2-4 times higher than that of coarse grained metals [1]. However, their uniform elongation is often low due to early plastic instability in the tensile test. In contrast, the post-uniform elongation is still large, which is one of the characteristic features of the UFG materials. In the present paper, the post-uniform deformation of an UFG-Al during the tensile test is discussed in detail by analyzing the change in the specimen shapes during tensile test [6].

2. Experimental Procedures

Fully annealed sheets of a commercial purity Al (AA1100) was used as the starting material in this study. The dimensions of the starting sheets were 1 mm in thickness, 55 mm in width and 220 mm in length. Two starting sheets were stacked after degreasing by acetone and wire-brushing the contact surfaces and then roll-bonded by 50% reduction in one pass without lubrication at ambient temperature. The roll-bonded sheet was immediately water-cooled after rolling. The rolled sheet was cut into half-length, trimmed and subjected to the next ARB cycle. This procedure was repeated up to 6 cycles (equivalent strain: $\varepsilon_{eq} = 4.8$) without changing the rolling direction (RD). Electron
backscattering diffraction pattern (EBSD) measurement in a scanning electron microscope equipped with a field emission-type gun (FE-SEM) was conducted for the starting material and the ARB-processed specimen. Observed sections for the EBSP measurement were perpendicular to the transverse direction (TD) of the sheets. The observed plane was electro-polished in a 30 vol% HNO₃ + 70 vol% CH₃OH solution at 243 K and voltage of 20 V. Tensile specimens with 10 mm in gage length and 5 mm in width were cut off from the starting material and the ARB-processed sheet. The tensile direction was parallel to RD. The images of the specimen were recorded continuously during the tensile test from normal direction and transverse direction of the sheet specimens by two digital video cameras. The schematic illustration of the hardware configuration for the specimen shape analysis system is shown in Fig. 1. The shape of the specimen was determined quantitatively by detecting the edge of the specimen in the images using software programmed by ourselves.

3. Results and Discussion

3.1. Microstructure

Figure 2 shows the grain boundary maps obtained by EBSD measurement of the starting material and the specimen ARB-processed by 6 cycles. In these maps, high angle grain boundaries (HAGBs) with misorientation angle above 15° are shown as black lines, while low angle grain boundaries (LAGBs) with misorientation angle between 2° and 15° are shown as gray lines.

The starting material shows the equiaxed grain structure having the mean grain size of 24 μm. On the other hand, the ARB-processed specimen showed the lamellar boundary structure elongated along RD. The mean spacing of all lamellar boundaries including low-angle ones were 220 nm.

Figure 2 Grain boundary maps obtained by EBSD measurement of (a) the starting material and (b) the ARB-processed specimen. Black lines indicate boundaries with misorientation of θ ≥ 15°, while gray lines indicate boundaries with misorientation of 2° ≤ θ < 15°.
3.2. Mechanical properties

Figure 3 shows the stress-strain curves of the starting material and the ARB-processed specimen. In this figure, gray curves indicate nominal stress while black curves indicate true stress calculated from the minimum cross-sectional area obtained from the specimen shape analysis. The starting material exhibits typical deformation behavior of the coarse grained metals. The ultimate tensile stress (UTS) was 84 MPa at the engineering strain of 33%. The total elongation was 49%. The strain at which necking in the width direction started was estimated as 31% by the specimen shape analysis, which approximately corresponded to the strain of the UTS. Necking in the thickness direction started at 39%. Then, the nominal stress decreased rapidly. True stress calculated from the minimum cross-sectional area was larger than the nominal stress and increased continuously even after necking. This result indicates that the necking region is continuously work-hardened during post-uniform deformation.

The ARB-processed specimen showed peak stress at early stage in the tensile test (Fig. 3 (b)). The UTS of the ARB-processed sample was 290 MPa at the strain of 4.5% and the total elongation was 11%. The strain at which necking in the width direction started was 4.9%, which almost coincided with the strain of the UTS. Necking in the thickness direction started at 6.5%, at which the slope of the nominal stress changed. True stress obtained by the specimen shape analysis decreased after necking in the width direction and increased after necking in the thickness direction, which was quite different from the result of the starting material. This result suggests that the necking region is not hardened but softened by deformation after the peak engineering stress. The softening might be caused by dynamic recovery. It is well known that the pure Al generally undergo dynamic recovery at ambient temperature because of the enhanced cross-slip of screw-dislocations due to its high stacking fault energy. In addition, the UFG materials have a large number of grain boundaries. It is likely that grain boundaries act as a sink for dislocations. This would help annihilation of dislocations and result in enhanced recovery. On the other hand, strain hardening after necking in the thickness direction is thought to be caused by high strain-rate sensitivity of the ARB-processed Al. Significant strain-rate dependence of the flow stress in the UFG materials has been reported [7-10]. In tensile test, strain-rate increases after necking because the deformation proceeds only within the necking region. Thus, the stress might increase when hardening caused by the increase in strain-rate is larger than the softening caused by the recovery in the necking region.

![Figure 3](image-url)  
**Figure 3** Stress-strain curves of (a) the starting material and (b) the ARB-processed specimen. Gray curves indicate nominal stress while black curves indicate true stress calculated from the minimum cross-sectional area obtained from the specimen shape analysis.
4. Conclusions
The deformation behavior of a commercial purity Al highly deformed by the ARB process was investigated by analyzing the change in the specimen shapes precisely. The major results obtained are summarized below:
(1) Commercial purity Al ARB-processed by 6 cycles showed the ultrafine lamellar boundary structure having mean lamellar spacing of 220 nm.
(2) Specimen shape analysis during the tensile test clarified that the strain at which the necking in the width direction started approximately coincided with the strain at the UTS in both the starting material and the ARB-processed specimen.
(3) True stress of the ARB-processed sample decreased after necking in the tensile test, while that of the starting material with the coarse grains increased. The softening of the ARB-processed Al might be caused by dynamic recovery at grain boundaries.

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