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Analysis of deformation behaviors of ultrafine grained Cu-30%Zn with bimodal grain-size distribution

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Abstract Ultrafine grained (UFG) metals have remarkably high strength in comparison with that of coarse grained metals. However, the UFG metals often exhibit low tensile ductility. It has been reported that the UFG metals having bimodal grain-size distributions consisting of coarse grains and fine grains perform large elongation keeping high strength. However, the exact deformation mechanism of the bimodal UFG metals has not yet been clarified. Deformation behaviors of a bimodal UFG metal were studied in the present paper. A sheet of Cu-30%Zn was highly deformed by accumulative roll-bonding (ARB) process and then annealed. The annealed specimen showed a fully-recrystallized UFG structure with a bimodal grain size distribution. To clarify deformation behaviors of the bimodal metal, an identical region was observed by the electron backscattered diffraction (EBSD) method at various tensile strains. The grain average misorientation (GAM) increased with increasing the tensile strain. The increase in GAM of the coarse grains was larger than that of the fine grains, suggesting the difference in local deformation and strain-hardening behaviors between different grain sizes. The enhanced uniform elongation of the bimodal UFG specimen was considered to be associated with the difference in strain-hardening between the coarse grains and fine grains.

1. Introduction

Ultrafine grained (UFG) metals with grain sizes smaller than 1μm have remarkably high strength in comparison with that of coarse-grained pure and even alloyed metals. However, the fine grained materials often exhibit low tensile ductility compared with the coarse-grained counterparts. On the other hand, it has been reported that the UFG materials having bimodal grain-size distributions consisting of coarse and fine grains perform large elongation keeping high strength [1, 2]. It has been explained that the fine grains maintain high strength of the material while the coarse grains produce large elongation. However, the exact deformation mechanism of the bimodal UFG materials has not yet been clarified. Thus, we investigated the contribution of the different grain sizes on tensile deformation behaviors, using a fully-recrystallized bimodal UFG material in this study.

2. Experimental Procedures

Chemical composition of a Cu-30%Zn used in the present experiments is shown in Table 1. The Cu-30%Zn sheet with a size of 200 × 40 × 1 mm^3 was highly deformed by the accumulative roll-bonding (ARB) process [3] with lubrication at room temperature up to 6 cycles, corresponding to an equivalent strain of 4.8, for making an UFG structure. After the ARB process, the Cu-30%Zn sheet was annealed at 250 °C for 5.4 ks to fabricate a fully recrystallized bimodal UFG structure.

An identical region of the tensile specimen was observed by the EBSD method in order to investigate deformation behaviors of the bimodal metal. The tensile test was stopped at 3.4%, 15% and 24.2% elongation, and the identical region was analyzed by EBSD. The grain average misorientation (GAM) [4, 5] is calculated in the following process. First, the misorientation between neighboring pairs of each measured point within the grain is calculated. Second, these misorientations are averaged in each grain surrounded by high-angle grain boundaries. The increase in GAM is considered to correspond to the development of the dislocation substructures within the grains. Consequently, the GAM is expected to be a parameter that indicates the amount of local strain.

Table 1. Chemical composition of the Cu-30%Zn (JIS2600P) studied (wt%).

	Cu	Pb	Fe	Zn
JIS2600P	69.26	0.0017	0.0073	Bal.

3. Results and Discussion

3.1. Microstructure and Mechanical properties

Figure 1 shows a grain boundary map of the Cu-30%Zn specimen ARB processed by 6 cycles and subsequently annealed at 250 °C for 5.4 ks. The specimen shows a fully recrystallized UFG structure composed of submicrometer UFGs and relatively coarse grains with several μm grain sizes. The mean grain sizes (in area) of the fine grains and coarse grains were 0.25 μm^2 (circle approximated diameter of 0.56 μm) and 10.7 μm^2 (circle approximated diameter of 3.7 μm), respectively. This fully-recrystallized bimodal structure is significantly different from the bimodal structure in the Cu specimen reported in [1, 2] that was composed of as-SPD (severe plastic deformation) processed UFG matrix and partially recrystallized coarse grains.

Figure 2 shows engineering stress-strain curves of the starting material, as-ARB processed specimen, and the specimen annealed at 250 °C for 5.4 ks after the ARB process (bimodal specimen). The tensile strength and the uniform elongation of the starting sample were 369 MPa and 53.4%, respectively. The tensile strength of the as-ARB specimen increased to 819 MPa, while the uniform elongation greatly decreased to 2.2%. The bimodal specimen showed the tensile strength of 516 MPa and uniform elongation of 24.4%. It can be concluded that the bimodal UFG structure performs a large tensile elongation keeping high strength.

3.2. Observations and Analysis of an identical region by EBSD

Figure 3 shows the IPF maps of the identical region in the tensile specimen obtained from the EBSD measurement for the Cu-30%Zn having the bimodal UFG structure. In the 16% tensile-tested specimen (figure 3(b)), the grains are elongated to the tensile direction (RD). The gradation of the color in the grains in figure 3(b) indicates that misorientation has appeared within individual grains. The color gradation in the coarse grains is more significant than that in the fine grains, which suggests that the coarse grains have larger misorientation than the fine grains.

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Figure 1. High angle grain boundary map obtained from the EBSD measurement of the Cu-30%Zn specimen ARB processed by 6 cycles and subsequently annealed at 250 °C for 5.4 ks.

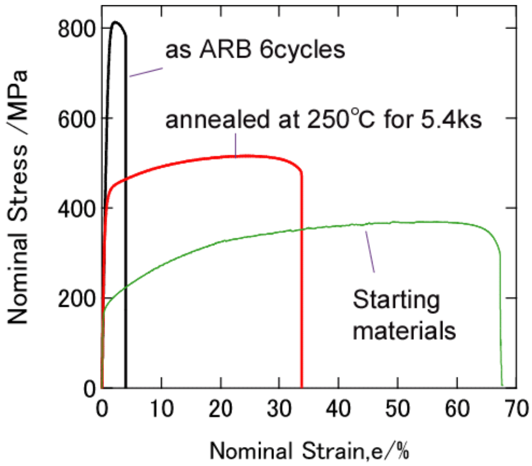

Figure 2. Nominal stress-strain curves of the starting material (Cu-30%Zn alloy), the as-ARB processed specimen, and the bimodal UFG specimen (ARB processed and then annealed at 250 °C for 5.4 ks).

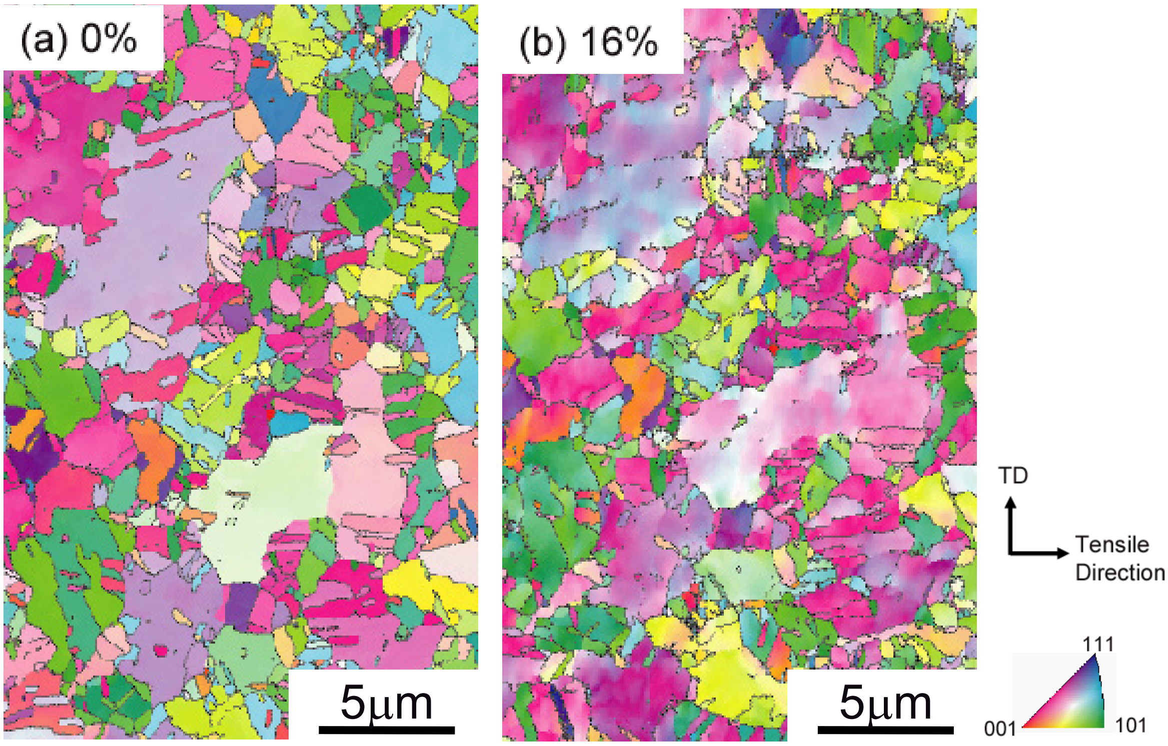

Figure 3. Inverse pole figure maps obtained from the EBSD measurement of the identical area in the bimodal UFG specimen (a) before tensile test and (b) after 16.0% tensile elongation.

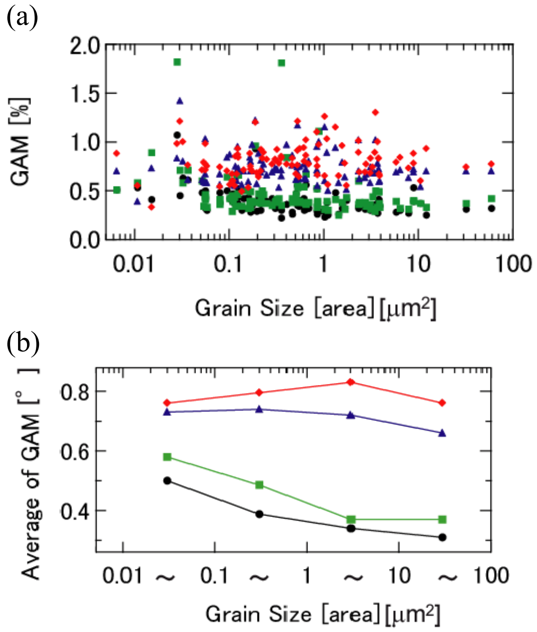

Figure 4. (a) GAM of the grains within the observed area shown in figure 3 as a function of the grain size (in area). The GAM values for the bimodal specimen before the tensile test, tensile-deformed to 3.4%, 24.2% and 16.0% are indicated in different marks with different colors, as is shown above. (b) Average GAM as a function of grain size (in area). GAM values were averaged within the ranges; 0.01 ~ 0.1 μm^2, 0.1 ~ 1 μm^2, 1 ~ 10 μm^2 and 10 ~ 100 μm^2.

Figure 4 (a) shows GAM values of the grains in the identical observed area shown in figure 3 as a function of the grain size (in area). The GAM increased with increasing the tensile strain for all grain sizes. In figure 4 (b), the GAM values were averaged within four grain size ranges; 0.01~0.1 μm^2, 0.1~1 μm^2, 1~10 μm^2 and 10~100 μm^2. The increase in the average GAM of the coarse grains (10~100 μm^2 range) is 0.45º, which is obviously larger than that of the fine grains in the 0.01~0.1 μm^2 range (0.26º). The larger increase in GAM is considered to correspond to the more significant development of the dislocation substructures within the grains. The result thus suggests that the coarse grains are more strain-hardened than the fine grains in the present bimodal UFG structure. The enhanced uniform elongation of the bimodal UFG specimen might be associated with the difference in strain-hardening between the coarse grains and fine grains.

4. Summary

A fully recrystallized bimodal UFG structure was obtained in a Cu-30%Zn alloy through ARB and subsequent annealing processes. The EBSD measurement of an identical region in the tensile specimen indicated that the development of misorientation within the coarse grains is larger than that within the fine grains during tensile deformation. This suggests the difference in strain-hardening between the coarse grains and fine grains, which are considered to be attributed to the large elongation keeping high strength in the bimodal UFG specimen.

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