Deformation and Recrystallization in Lightly-Rolled Aluminum Single Crystals of Cube Orientation*1

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Deformation and recrystallization of 17%- and 34%-rolled aluminum single crystals of cube orientation were studied. Most slip bands observed in the TD surface were straight and the occurrences of cross-slip were small. There was a relatively large orientation variation in the TD surface and the deviation from the initial orientation reached 10° in the 34%-rolled sample. After annealing, recrystallized grains were formed both at the rolled surfaces and around the middle of the thickness of the sample. Two thirds of the recrystallized grains had (111)-rotation relationships with the deformed matrix. Although all (111)-rotation relationships were found, their occurrences were not the same. Above results are compared with those obtained in tensile-deformed aluminum single crystals with the same initial orientation.

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1. Introduction

In order to study the relationship between deformation microstructure and recrystallization from fundamental viewpoint, it is useful to conduct experiments using orientation-controlled single crystals and bicrystals as samples.1-3) Inoko and coworkers4-14) have long been studying the deformation and recrystallization of tensile-deformed aluminum single crystals and bicrystals. They have recently found close correlation among slip morphology, cell structure, work-hardening and recrystallization behavior of aluminum single crystals tensile-deformed along the (001), (111) or (112) direction in which macroscopic deformation was uniform without the formation of deformation bands due to the balanced activation of multiple slip from the initial stage of plastic deformation.15-18) Most interesting results were the temperature dependence of cross-slip and its influence on deformation microstructure, work-hardening and recrystallization in single crystals tensile-deformed along the (001) direction.15,18) (The tested single crystals had a rectangular gauge portion. For the tensile direction of [001], the front and side surfaces of the sample were indexed as (100) and (010), respectively. In the following, such single crystals are referred to as (001) single crystals. We should note that they have the same orientation as the single crystals with cube orientation in rolling.) When deformed at room temperature (RT), slip bands were wavy and frequent cross-slip was activated with large step height approximately of 100μm. The cell structure observed by transmission electron microscopy (TEM) was characterized by large cell size approximately of 5μm in diameter and cell walls with very low dislocation density. The work-hardening rate was very small. The deformation stress reached a saturated value of 20 MPa at a tensile strain of 0.04. The nominal stress at a strain of 0.25 was only 22 MPa. Such small work-hardening was due to stress relaxation caused by cross-slip with large step height. After annealing, no recrystallized grain was formed. Since cross-slip is a thermally activated phenomenon, deformation behavior of aluminum (001) single crystal drastically changed when the deformation temperature was lowered to the liquid nitrogen temperature (LNT), 77 K. Cross-slip with large step height was completely suppressed. Dislocation density was raised and the average cell size was as small as 2μm at a strain of 0.2. As a result, the work-hardening rate was very large. The nominal stress reached 106 MPa at a tensile strain of 0.2, about five times as large as that observed in RT deformation. After annealing, the (001) single crystal recrystallized. Most recrystallized grains (RGs) had (111)-rotation relationships with the deformed matrix, that is, RGs were related to the matrix orientation by rotations about (111)-axes.19-23) As described above, there is a close relationship between recrystallization and deformation microstructure, e.g. morphology of slip bands and cells. The major objective of the present study is to observe the deformation microstructure and annealing behavior of lightly rolled aluminum single crystals of cube orientation. Comparison is made with the results of tensile-deformed (001) single crystals.

2. Experimental Procedures

Aluminum single crystals were grown using a Bridgman method. The purity of the starting material was 99.99 mass%. Samples of the cube orientation were spark-cut from the grown single crystals. The surface of the samples was mechanically polished and subsequently mirror-finished by electrolytic polishing. The stereographic projection of the initial orientation of the samples is presented in Fig. 1 along with their schematic. In the stereographic projection, the poles of {111} slip planes and (110) slip directions are indicated by triangular symbols P1 through P4 and elliptic symbols D1 through D6, respectively (In the following sections, in order to represent (111)-axes, we use terms such as P1-axis, P2-axis.). RD, ND and TD are the abbreviation of
rolling, normal and tangential directions, respectively. The deviation of the initial orientation from the ideal cube orientation was within $1^\circ$. Two samples were prepared. Rolling of 17% and 34% was applied to the samples. Each rolled sample was cut into two pieces. Thin foils for TEM observation were prepared from one of the pieces. Slip band observation and local orientation measurement were made in the TD surface of the other piece using a scanning electron microscopy (SEM)/electron channeling pattern (ECP) method. Annealing was conducted at a fixed temperature for duration of 150 to 240 s and then repeated at higher temperatures until RGs were obtained. The orientations of RGs were determined by a SEM/ECP method.

3. Results

3.1 Deformation

After rolling, slip band observation was made on the TD surface of the sample. General feature of slip bands was almost the same, irrespective of the positions in the TD surface, except for the regions close to the rolled surfaces. SEM images of slip bands taken in the middle of the TD surface are presented in Fig. 2. Although the slip band density in the 34%-rolled sample (Fig. 2(b)) is larger than that in the 17%-rolled sample (Fig. 2(a)), appearances of slip bands in both samples look alike. Most slip bands are not so wavy with low frequency of cross-slip. In Fig. 2(a), a typical cross-slip is indicated by a circle. The largest step height of cross-slip found in the present samples was about 15 $\mu$m.

Such cross-slip behavior is dissimilar to that observed in aluminum (001) single crystals tensile-deformed at RT.\(^{15}\) Also, the slip morphology of the present samples is dissimilar to that observed in aluminum (001) single crystals tensile-deformed at LNT in which slip bands were very fine due to cross-slip with very small step height approximately of 2 to 3 $\mu$m.\(^{15,18}\)

To study the orientation change associated with deformation, the orientations of randomly chosen four points in the 17%-rolled sample and six points in the 34%-rolled sample were measured with a SEM/ECP method. The results are plotted in (111) pole figures in Fig. 3. In the 17%-rolled sample (Fig. 3(a)), the deviation from the initial orientation was about $5^\circ$. On the contrary, in the 34%-rolled sample (Fig. 3(b)), the deviation was about $10^\circ$. In tensile-deformed (001) aluminum single crystals, because of balanced activation of eight slip systems on four slip planes, the deviation from the initial orientation was small, less than $4^\circ$ even in single crystals with a tensile strain of 0.3.\(^{18}\) The large orientation deviation in the 34%-rolled sample suggests that the activations of slip systems were different.

TEM images of the cell structures of the rolled samples are presented in Fig. 4. In both 17%-rolled (Fig. 4(a)) and 34%-rolled (Fig. 4(b)) samples, observation was made along the
TD. In the 17%-rolled sample, dislocation density was low and the average cell size was 4 to 5 µm, which is a similar value for a (001) aluminum single crystal tensile-deformed to a strain of 0.25 at RT. However, both microstructures are not the same. Unlike round-shaped cells in tensile-deformed (001) single crystals, cells elongated along the slip traces are found in the 17%-rolled sample. In other words, the microstructure of the 17%-rolled sample is anisotropic. This feature is more pronounced in the 34%-rolled sample. With the decrease in the average cell size to about 3 µm, the degree of anisotropy in cell structure increased with rolling.

3.2 Recrystallization

The 17%-rolled sample recrystallized at the rolled surfaces after three-stage annealing, i.e. 583 K–180 s, 643 K–180 s and 683 K–180 s. As described in the previous section, deformation in the regions close to the rolled surfaces was complex due to the friction from the roller. Hence, the forth-stage annealing was conducted at 713 K for 240 s to obtain RGs in the region apart from the rolled surfaces. An optical micrograph of the TD surface of the sample is presented in Fig. 5. Twenty-one RGs were formed around the middle of the thickness of the sample. The orientations of the 21 RGs were measured with a SEM/ECP method and compared with the orientation of the deformed matrix. Two thirds of the RGs (14 RGs/21 RGs) had ⟨111⟩-rotation relationships with the matrix, that is, RGs were rotated about P1-, P2-, P3- and P4-axes. The orientations of such RGs are plotted in ⟨111⟩ pole figures in Fig. 6. We should note that the occurrences are not the same.

In the 34%-rolled sample, RGs were formed at the rolled surfaces after three-stage annealing, i.e. 673 K–180 s, 693 K–180 s and 713 K–180 s. Additional annealing was conducted at 713 K for 510 s. An optical micrograph of the recrystallized TD surface is presented in Fig. 7. Eighteen RGs were
RGs with respect to the deformed matrix are much larger. We consider that the recrystallization mechanism similar to that in tensile-deformed single crystals acted in the lightly rolled samples.

5. Summary

Slip morphology, deformation microstructure and recrystallization were studied in 17%-rolled and 34%-rolled aluminum single crystals of cube orientation. The results were compared with those obtained in aluminum single crystals having the same orientation. Unlike tensile-deformed single crystals, slip bands were almost straight with small occurrences of cross-slip. Orientation variation within the deformed microstructure increased with rolling; about 10° in the 34%-rolled sample. After annealing, recrystallization occurred at the rolled surfaces and around the middle of the thickness of the rolled sample. Two thirds of the RGs were formed through (111)-rotation mechanism.

REFERENCES