# ORIENTATION RELATIONSHIPS BETWEEN RECRYSTALLIZED GRAINS AND MULTIPLE SLIPPED STRUCTURE IN ALUMINUM SINGLE CRYSTALS

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**ABSTRACT** Dislocation structure and recrystallization behavior in aluminum single crystal with a tensile axis (TA) of <111>, in which multiple slips occur without the formation of deformation bands(DBs), are investigated. Orientation relationships between recrystallized grains(RGs) and deformed matrix(DM) (originally multiple slipped structure) are analyzed on the basis of the <111> rotation mechanism, which is derived from interactions of dislocation loops introduced in deformation. It is well demonstrated that the formation of the RGs with <111> rotation relationships to the DM in the multiple slipped structure is explained by the mechanism.

**Keywords:** tensile deformation, slip system, dislocation structure, dislocation loop, primary recrystallization, <111> rotation, orientation relationship

## 1. INTRODUCTION

Tensile deformation behavior in fcc single crystals strongly depends on the initial TA orientations of the crystals[1]. During deformation, multiple slips take place in crystals with specific TA orientations, for example, <111> and <001>. Remarkable cross slips are not observed at all in <111> crystals, however, in <001> crystals cross slips readily occur. It is also known that dislocation structure in <111> crystal deformed in tension is quite different from that in <001> one[2]. <111> crystal shows layered dislocation structure, whereas <001> crystal pseudo-isotropic cell structure. Recrystallization in the single crystals also inherits the initial TA orientation dependence[3]. Under the same annealing condition, RGs in <111> crystal can be formed at lower temperature and shorter time than those in <001> one, because the occurrence of cross slips reduces dislocation density to store in the crystal at least in deformation.

In aluminum single crystals accompanied with the formation of DBs, individual RGs tend to take <111> rotation relationships to DM[4]. A recrystallization nucleation model, which was based on interactions of dislocation loops introduced by slip systems activated in deformation, was proposed to rationalize the formation of the RGs with <111> rotation relationships. The formation could be well explained by the nucleation model hereafter called "<111> rotation mechanism". In the present study, recrystallization behavior in aluminum single crystal specimen with multiple slips without DBs is investigated. Selections of <111> rotation axes of the RGs to the DM are compared with the estimation on selections of <111> rotation axes of the RGs using the <111> rotation mechanism.

## 2. EXPERIMENTAL PROCEDURES

Aluminum single crystal specimens (purity 99.99mass%) with a TA orientation of <111> were prepared. The available size of the specimens was about 7x3.5x10mm$^3$. A stereographic projection at the initial orientation of <111> specimen was indicated in Figure 1. Four {111} slip planes were named "P1", "P2", "P3" and "P4" and six <011> slip directions "D1 " to "D6". A symbol P1D1 indicates a slip system of a slip plane P1 and a slip direction D1. For example, $P\bar{1}D\bar{1}$ means the inverse plane and direction to P1D1. <111> specimens were deformed in tension to a strain of 0.22 with a strain rate of 3x10$^{-4}$s$^{-1}$ at room temperature. Deformed dislocation structure parallel to (211) was examined using a Hitachi-H800 transmission electron microscope(TEM) at 200kV. Another deformed <111> specimen was annealed under a condition of 753K-1500s in an ambient atmosphere.

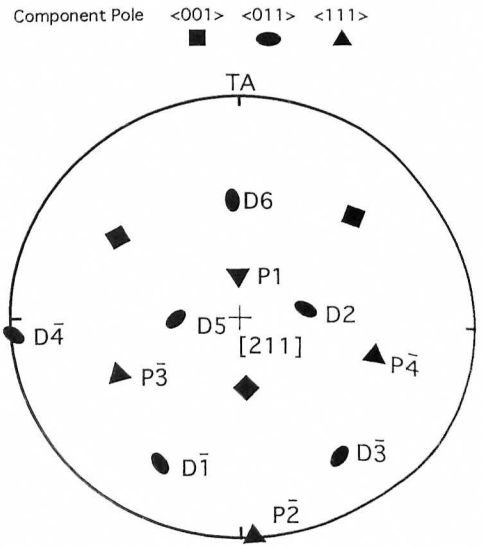


Figure 1 A stereographic projection of the initial orientation of single crystals.

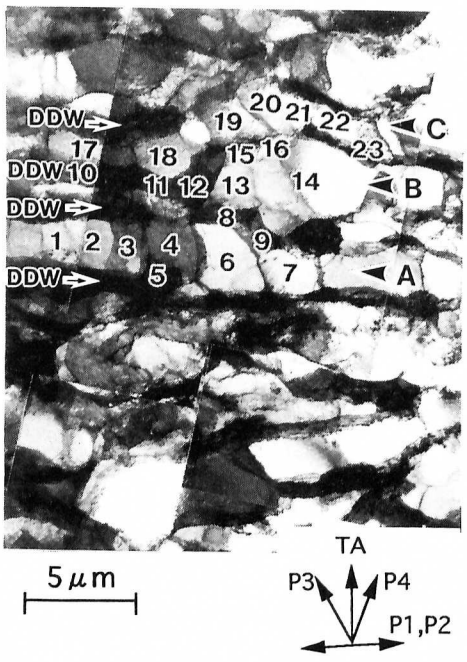


Figure 2 A TEM micrograph of the specimen deformed in tension to a tensile strain of 0.22.

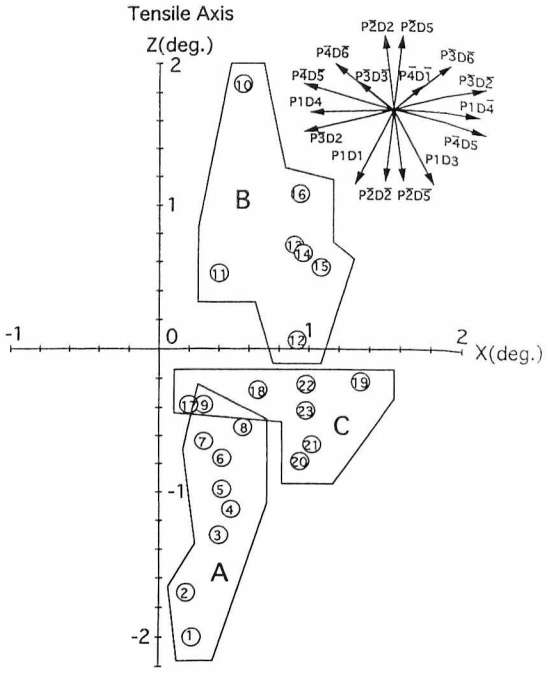


Figure 3 [211] orientations of the twenty-three cells. The origin for axes Z and X is normal to the observed plane.

The recrystallized structure was observed using a JOEL JSM-6400 scanning electron microscope (SEM). Orientations of the RGs were analyzed from electron channeling patterns(ECPs).

## 3. EXPERIMENTAL RESULTS

Figure 2 shows a TEM micrograph of as-deformed dislocation structure. At the strain of 0.22, a layered dislocation structure was developed, especially dense dislocation walls (DDWs)[5] with wavy shapes in a direction of P1 or $P\bar{2}$ were seen. The orientations of twenty-three cells were measured and the corresponding [211] orientations are shown in Figure 3. They are indicated as deviations from an orientation perpendicular to the observed plane. Axes "Z" and "X" are parallel to the observed plane. And they also are parallel to the TA and normal to the TA, respectively. An illustration of sixteen arrows with the symbols of slip systems represents the geometric rotation directions of the cells when the corresponding slip systems are operated. The slip systems with longer arrows are able to produce the larger rotations of the cells, seeing from the observed plane. The orientations obtained were mainly classified into three groups of A to C, which were divided by the DDWs. They seemed to be mutually rotated around the axis X as if they have undergone compression and tension by turns. The slip systems effective to produce the larger rotations around the axis X are P1D1 and P1D3, which actually showed the strongest operations in macroscopic observation using SEM[6]. P2D2 and P2D5 can also produce the large rotations, assuming that Schmid factors of the slip systems are ignored. The maximum misorientation among the twenty-three cells was approximately 4 degrees around the axis X.

Figures 4 shows a recrystallized structure and the corresponding schematic illustration. RG numbers were given to the individual RGs. The percentages recrystallized was approximately 80%. The RGs recognized was sixty-three, whose a mean diameter was about 1.13mm. 71% of

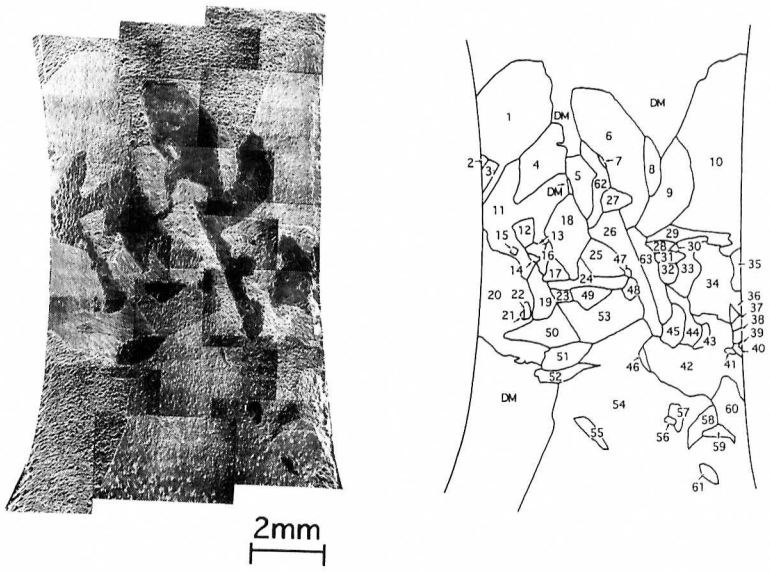


Figure 4 A recrystallized structure annealed at 753K-1500s (a) and its schematic illustration (b).

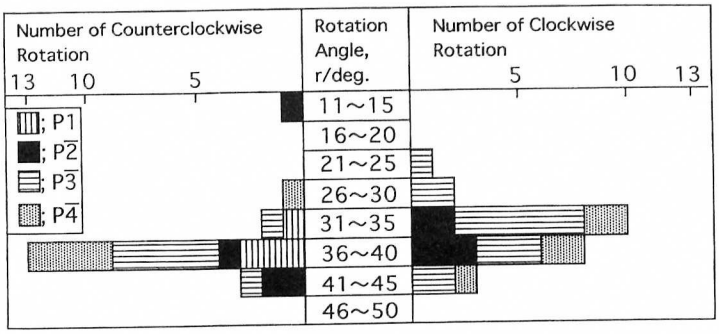


Figure 5 A line graph on rotation angles and directions of RGs with one of four <111> rotation relationships to DM.

the RGs in number were rotated around one of four <111> rotation axes of the DM. Figure 5 shows a line graph on the rotation angles and directions of the RGs with <111> rotation relationships. Most of RGs were rotated over 26 degrees. The peaks were the ranges from 31 to 35 degrees clockwise and 36 to 40 ones counterclockwise. Here we have to recollect that in the TEM observation the cells with such large misorientations around the <111> axes were not distinguished at all in the deformed structure. The maximum misorientation in the deformed structure was 4 degrees, and moreover, in the macroscopic observation it was within 5 degrees[6]. Therefore it

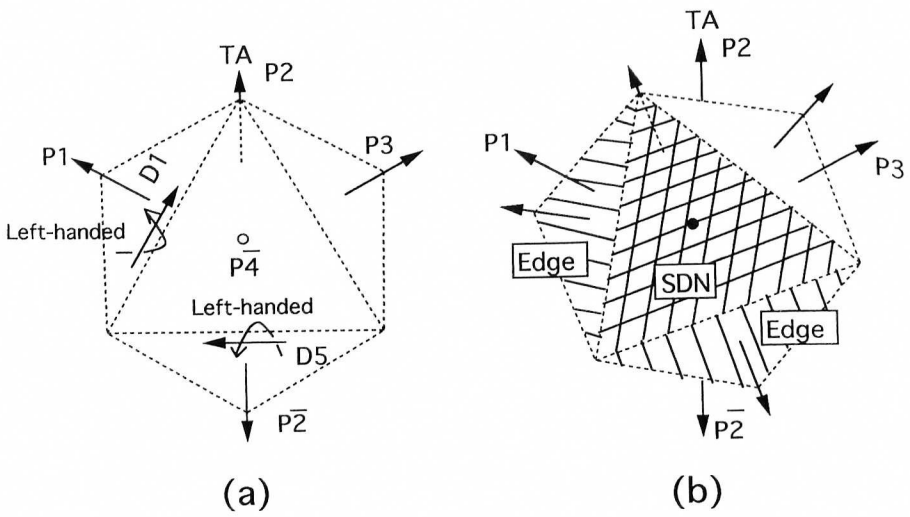


Figure 6 Schematic illustrations for interaction of dislocation loops introduced by two slip systems: (a) two left-handed screw dislocations introduced on a common cross slip plane P4̄, (b) a latent solid dislocation loop consisted of a screw dislocation network on P4̄ and arrays of edge dislocations on P1 and P2̄. SDN means screw dislocation network.

found that the recrystallization in multiple slipped structure is followed by neither the "bulging theory"[7] nor the "strain (or deformation) induced boundary migration (SIBM) theory"[8].

According to the <111> rotation mechanism[4], for example, in order to form a RG rotated around an axis normal to $P\bar{4}$ at least two slip systems among P1D1, P2D5 and P3D6 need to operate. We consider interactions of dislocations on P1, $P\bar{2}$ and $P\bar{4}$ to simplify the explanation. Figure 6 is schematic illustrations showing the interactions of dislocation loops introduced by P1D1 and P2D5 on $P\bar{4}$. The dislocation loops introduced by their operations react to form a screw dislocation network on their common cross slip plane($P\bar{4}$) and arrays of edge dislocations on their own slip planes(P1 and $P\bar{2}$), if the same signs of the screw dislocations are introduced (left-handed screw dislocations). Then the screw dislocation network on $P\bar{4}$ will result in the twist boundary to the surrounding DM. Thereby, seeing from the observed plane, a latent solid dislocation network consisted of the screw dislocation network and arrays of edge dislocations would be able to rotate counterclockwise around the axis normal to $P\bar{4}$ during recovery and recrystallization processes. In result, a RG of $P\bar{4}$, which originated from the latent solid dislocation network, can be developed. The direct evidence to verify this mechanism have not been obtained yet, however the pertinence of the <111> rotation mechanism must be ascertained by a comparison between the estimation and the evidence actually obtained on the selections of <111> rotation axes of the RGs in number. If the estimation corresponds with the evidence on the selections of <111> rotation axes, the <111> rotation mechanism will be available for the RGs with <111> rotation relationships formed in the multiple slipped structure.

To ascertain the pertinence of the <111> rotation mechanism, let us compare the estimation with the evidence obtained on the selection of <111> rotation axes of the RGs. Table 1 shows the result on the selection of <111> rotation axes actually obtained and the estimation on the selections based on the <111> rotation mechanism. Since the mechanism is derived from interactions among dislocation loops introduced by slip operations in deformation, the activities of individual slip systems need to be estimated. In the present study, it was carried out from the result of the TEM observation. A mark "+" means the degree of activity of each slip system; the more the mark "+" the higher the activity of slip system. A mark "—" denotes that the slip system is hard to activate.The activities among the slip systems are relative not absolute. The slip systems P1D1,

Table 1 Actual evidence and estimation on selections of <111> rotation axes in RGs.

| <111> Rotation Axis | P1 | $P\bar{2}$ | $P\bar{3}$ | $P\bar{4}$ | Unknown |
|---|---|---|---|---|---|
| Slip System and Activity | P2D4 —<br>P3D3 —<br>P4D1 — | P1D4 —<br>P3D2 —<br>P4D5 — | P1D3 ++<br>P2D2 ++<br>P4D6 + | P1D1 ++<br>P2D5 ++<br>P3D6 + | |
| Estimation on Selection of <111> Rotation Axes | Suppressed | Suppressed | Facilitated | Facilitated | |
| Actual Evidence on the Selection in number | 4 | 9 | 21 | 11 | 18 |

P1D3, P2D2 and P2D5 were ranked as "++", because they were the most effective slip systems to produce the rotations. The detailed discussion on the activities of P2D2 and P2D5, which have basically low Schmid factors, will be described elsewhere[6]. P3D6 and P4D6 were as "+" because of the second effective ones, and the other four slip systems as "—". Considered the activities of the corresponding three slip systems to form RGs with each <111> rotation axis, the formations of RGs with $P\bar{3}$ and $P\bar{4}$ axes will be facilitate in number. On the other hand, those with P1 and $P\bar{2}$ will be suppressed because the corresponding slip systems were ranked as "—".

The actual evidence on the selections of <111> rotation axes shows that twenty-one RGs of $P\bar{3}$ had the highest value. The number of RGs of $P\bar{4}$ was eleven, which was the second one. Those of $P\bar{2}$ and P1 were nine and four, which were the third and the fourth, respectively. Thus, the actual tendency of distribution of the selections on the formation numbers of RGs with four <111> rotation relationships corresponds well with the estimation on the selections of <111> rotation axes derived from the activities of slip systems. Especially, RGs of $P\bar{3}$ and $P\bar{4}$ were predominately formed, whereas the formation of RGs of P1 was comparatively suppressed. From these results, it is can be concluded that the formation of the RGs with <111> rotation relationships in the multiple slipped structure without DBs is followed by the <111> rotation mechanism rather then other theories[7][8].

## 4. CONCLUSIONS

The deformation and recrystallization behaviors in the aluminum single crystals with TA orientation of <111> were investigated, in which multiple slips occur without formation of DBs. At the strain of 0.22, the layered dislocation structure are developed. The cells are rotated around the axis normal to the TA, as if they have undergone compression and tension by turns. The main orientation relationships between the RGs and the DM (originally multiple slipped structure) are one of four <111> rotation relationships. It is found that the formation of the RGs in the multiple slipped structure is explained by the <111> rotation mechanism, which is derived from interactions of dislocation loops introduced during deformation.

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