On the development of a model predicting the recrystallization texture of aluminum using the Taylor model for rolling textures and the coincidence lattice site theory

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Abstract. First, hardening model in f.c.c. metals was formulated with collinear interactions slips, Hirth slips and Lomer-Cottrell slips. Using the Taylor and the Sachs rolling texture prediction model, the residual dislocation densities of cold-rolled commercial pure aluminum were estimated. Then, coincidence site lattice grains were investigated from observed cold rolling texture. Finally, on the basis of oriented nucleation theory and coincidence site lattice theory, the recrystallization texture of commercial pure aluminum after low-temperature annealing was predicted.

1. Introduction
Polycrystalline metals generally recrystallize both from grain boundaries, called strain-induced boundary migration, and from microbands or shear bands. A general mechanism of recrystallization from stored energy has been proposed. On the basis of a nucleation theory, cube orientated grains recrystallize from a bandlike structure formed during rolling[1]. The orientation of the recrystallized grain must exist within the spread of orientations present in the deformed state[2]. Recrystallization texture prediction models of b.c.c. metals have been proposed using the Taylor factors and total amount of microscopic slips based on the oriented nucleation model[3]-[4]. However, few recrystallization texture prediction models of f.c.c. metals have been proposed[5]-[6]. Many studies have been carried out on the formation of recrystallization textures in aluminum alloys and recrystallization textures of aluminum have not been analyzed as the Taylor factors. Furthermore, after primary recrystallization, two types of grain growth models are developed, one is based on a grain boundary character theory[7]-[8] and the other is based on a <111> 40° rotation theory[9]-[10]. Thus, hardening model considering collinear interaction slips[11]-[12] and sessile slips was formulated to estimate the density of accumulated dislocations in f.c.c. metals. For a while, many precise models have been proposed to predict rolling texture of f.c.c. metals[13]-[15]. Then, using the Taylor and Sachs deformation texture prediction model, dislocations at grain boundaries of pure aluminum was quantified. Next, coincidence site lattice grains were investigated from observed cold rolling texture. Recrystallization prediction model that depended on strain-induced boundary migration and coincidence lattice theory was developed.

2. Recrystallization texture prediction model
2.1. Hardening model of f.c.c. metals
Many hardening model of f.c.c. metals were proposed[16]-[17]. Inoko proposed tensile and compression cross slip models of aluminum[18]. We guess that this phenomena is the same as collinear interaction slips[11]. When a single aluminum crystal is stretched in the <100> direction, two slip systems cross in the same direction. This slip is called repulsive collinear interaction slip. On the other hand, when a single aluminum crystal is stretched in the <111> direction, two slip systems cross in the opposite directions. This cross slip is called attractive collinear interaction slip. Figure 1 shows slip system analysis of <001>-direction-stretched and <111>-direction-stretched single crystals of f.c.c. metals. By adding attractive collinear interaction slips, the total number of collinear interaction slips was estimated as

\[ \gamma_{\text{collinear}} = \sum \gamma_{\text{attractive}} \] (1)
Adding collinear interaction slips ($\Gamma_{\text{collinear}}$), Lomer Cottrell slips ($\Gamma_{\text{lomer}}$) and Hirth lock slips ($\Gamma_{\text{hirth}}$), the number of accumulated dislocations was estimated using equation (2). Coefficient of equation (2) was referred from Devincrea’s research[12].

\[
\Gamma = \Gamma_{\text{collinear}} + \Gamma_{\text{lomer}}/5 + \Gamma_{\text{hirth}}/10
\]  
\[
\tau_y = 13.0\sqrt{\Gamma}
\]

Figure 1: Attractive and repulsive collinear interaction slip of f.c.c. metals

Obeying equation (3), critical resolved shear stress ($\tau_y$) was calculated. Figure 2 shows stress-strain curve prediction accuracy of a single f.c.c. crystal.

2.2. Rolling texture analysis

The plastic strain rate $D^p$ and plastic spin $W^p$ can be defined using Eqs. (4) and (5).

\[
D^p_{ij} = \dot{\gamma}(a_i b_j + a_j b_i)/2 = P_{ij} \dot{\gamma}, \tag{4}
\]

\[
W^p_{ij} = \dot{\gamma}(a_i b_j - a_j b_i)/2 = Q_{ij} \dot{\gamma}, \tag{5}
\]

where $\dot{\gamma}, a, b$ and $P_{ij}$ are the slip rate, the unit vector normal to the slip plane and the unit vector in the slip direction, respectively. The f.c.c. crystal lattice has 12 slip systems. The strain equilibrium, the resolved shear stress of each slip system, the rate-dependent rule and boundary condition are expressed using Eqs. (6)-(9), respectively. Equation (6) implies that the sum of the slip values, $\gamma^{(k)}$, multiplied by $P_{ij}^{(k)}$ for each slip system in a crystal is equal to the sum of the microstrains $\varepsilon$. Equation (7) gives the relationship between the microstress $\sigma$ and the resolved shear stress $\tau^{(k)}$ acting on the slip plane. Equation (8) is the Asaro rate-dependent rule and $m$ is a material parameter. For the boundary conditions, the microstrain $\varepsilon$ is assumed to be equal to the macrostrain $E$ in accordance with the Taylor theory, as shown in Eq. (9). Here, $k$ is number of slip system.

\[
d\varepsilon_{ij} = \sum P_{ij}^{(k)} d\gamma^{(k)} \tag{6}
\]

\[
\tau^{(k)} = \sum \sum P_{ij}^{(k)} \sigma_{ij} \quad (i,j = 1,2,3) \tag{7}
\]

\[
d\gamma^{(k)} = \dot{\gamma}_0 \ast \frac{dt}{\tau_y} \ast \text{sign}(\tau^{(k)}) \tag{8}
\]

\[
\varepsilon = E \tag{9}
\]

where, $\dot{\gamma}_0, \tau_y$ and $dt$ are the reference slip strain rate, the critical resolved shear stress and the time increment, respectively. The critical resolved shear stress can be expressed as

\[
\tau_y = S / M \tag{10}
\]
where $M$ is the average Taylor Factor for all orientations and $\bar{\Sigma}$ is equivalent flow stress. The Newton Raphson method was used to resolve equations (6)-(9) as the microstress tensor $\sigma$ was unknown and the initial microstress tensor $\sigma_0$ is assumed to be equal to the macrostress tensor $\bar{\Sigma}$. However, when the microstress was not resolved, the Sachs boundary condition was used. For the boundary conditions, the microstress $\sigma$ is assumed to be equal to the macrostress $\bar{\Sigma}$ in accordance with the Sachs theory, as shown in Eq. (11).

\[ \sigma = \bar{\Sigma} \]  

(11)

Because using combined the Taylor model and the Sachs model, rolling texture prediction accuracy was almost good as shown in Figure 3.

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**2.3. Recrystallization texture analysis**

Next, coincidence site lattice grains were investigated from observed cold rolling texture. Figure 4 shows coincidence site lattice analysis[19]. Grains in black had coincidence site lattice boundaries such as $\Sigma 5, \Sigma 7, \Sigma 13$. Figure 5 shows that selection result of grains which had coincidence site lattice boundaries from rolling grains measured by EBSD. Recrystallization texture of aluminum was not predicted only by the CSL theory.

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Figure 3: Rolling texture prediction accuracy of f.c.c. metals

Figure 4: Coincidence site lattice (CSL) analysis (Left :observed, Right: analyzed)

Figure 5: Observed and predicted recrystallized aluminum texture by CSL model

Strain-induced grain boundary migration starts from the boundaries of grains with a large dislocation density difference[20]-[21]. In accordance with the number of dislocations given by equation (2), grains with high dislocation densities were encroached on grains with low dislocation densities. Succeeding the oriented nucleation theory, selective growth theory was introduced. First, grains with a small number of accumulated dislocations were selected using the oriented nucleation model. Next, grains with the special coincident lattice shown were selected in seven types of low grain boundary energies, namely $<100>$ and $<111>$. [22].
Figure 6 shows the observed and predicted recrystallization textures. In our predicted recrystallized texture in Fig. 6, each grain is drawn as a dot and all grains are assumed to be of the same size. Employing the universal recovery theory[23], our recrystallization texture prediction accuracy will be improved. However, the recrystallization texture observed by EBSD was almost in agreement with our predicted recrystallization texture.

3. Discussion of recrystallization texture

Many researchers have indicated that grains with <111> 40° rotation from a deformed matrix have high mobility. From the S orientation to the Cube orientation, the axis and angle of rotation are <1.08, 1.00, 1.23> and 48.6°, respectively and from the S orientation to the R orientation, <1.08, 1.00, 1.19> and 169.1°. Coincidence site lattice theory is ruled by the Brandon allowance. For example, one of 7 coincident lattices is <111> 38.2° and the Brandon allowance of an ideal coincident lattice was 5.7°, as calculated from

\[ V_m = 15 \times \Sigma^{0.5} \]

Sabin suggested that a combination of oriented nucleation and growth occurs in growth selection[24]. Engler observed the characteristics of both oriented nucleation and growth in obtained textures[25-26]. Our prediction model showed the same manner of grain selection with a small number of accumulated dislocations and the selective growth of grains with a coincident lattice.

4. Conclusions

The recrystallization texture of commercial pure aluminum was proposed on the basis of the number of accumulated dislocations calculated using the Taylor and the Sachs rolling texture prediction model with collinear interaction slips and sessile slips and using grain boundary characteristics. The prediction accuracy for the texture of cold-rolled and annealed aluminum was reasonable. To improve the prediction accuracy of recrystallization texture, grain-hardening model and rolling texture prediction model must be modified. And grain migration rule will be more precisely quantified.

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Figure 6: Observed and predicted recrystallized aluminum texture