Modeling of recrystallization texture of aluminium: symmetric and asymmetric rolling

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Abstract. In some metallic materials the dominating recrystallization mechanism can be described by the oriented growth behaviour. Phenomenological laws state that in selected materials only these nuclei grow intensively which have a given misorientation relation with the deformed matrix. This description is frequently verified in f.c.c. metals and generally reported misorientations correspond approximately to 40° rotation around the <111> axis. Basing on the above ideas the recrystallization model, including the compromise condition, was formulated and applied to the study of recrystallization textures of rolled polycrystalline aluminium.

1. Introduction

Texture development in f.c.c. metals was studied and described in the literature using various kinds of models (e.g., [1-5]). In some of these models the stored elastic energy (and residual stresses) play the essential role (e.g., [5-9]). However, a relatively simple orientation relation between growing nuclei and deformed matrix was found in aluminium, which can explain the formation of its recrystallization texture. Preferred misorientations, \( \Delta g \), between nuclei and deformed grains, correspond to high mobility of grain boundaries. They are traditionally described as a rotation \( \omega_0 \approx 40° \) around one of <111> axes. Therefore, the migration rate of grain boundary, \( u \), between a nucleus and the deformed matrix depends very strongly on misorientation \( \Delta g \). This relation was reported in [10] and [11]. Based on the above assumptions, a successful recrystallization model was formulated [5, 12]. It was also shown that predicted results are much improved if the so called compromise condition and, consequently, the compromise function are used. The proposed model was used to predict recrystallization textures of symmetrically and asymmetrically rolled aluminum alloys: Al-0.007% Fe and Al 6061. Let us describe now in more details the recrystallization model used in the present calculations.

2. Recrystallization model

2.1. Boundary migration rate

Each deformed grain is statistically consumed by many nuclei but with very different rates. The crystal misorientation \( \Delta g_{ij} \) between the nucleus \( i \) and the deformed grain \( j \) is expressed by the rotation axis \( \mathbf{r}_{ij} \) and the misorientation angle \( \omega_{ij} \). Obviously, in general a determined rotation axis \( \mathbf{r}_{ij} \) for a given misorientation \( \Delta g_{ij} \) does not exactly coincide with one of <111> axes; let us assume that it makes the angle \( \omega_{ij} \) with the nearest <111> axis of. Similarly, the \( \omega_{ij} \) misorientation angle does not equal exactly to \( \omega_0 \) (where \( \omega_0 \) corresponds to the maximum
migration rate). Therefore, basing on the results presented in [10] and [11] the boundary migration rate, \( u_{ij}(\omega_{ij}, \alpha_{ij}) \) between a nucleus \( i \) and a deformed grain \( j \), was approximated as:

\[
u_{ij}(\omega_{ij}, \alpha_{ij}) = u_{\text{max}} e^{-\frac{(\omega_{ij}-\omega_{0})^2}{\Delta \omega^2}} \cdot e^{-\frac{-\alpha_{ij}}{\Delta \alpha^2}}
\]

(1)

The first exponential function describes the dependence of migration rate on the misorientation angle \( \omega_{ij} \). In the second exponential function the effect of deviation of a current rotation axis \( \mathbf{r}_{ij} \) from the nearest <111> axis (\( \alpha_{ij} \) angle) is taken into account. In the above formula the following constants were adjusted from experimental data [12]: \( \omega_{0} = 40^\circ \), \( \Delta \omega = 13.7^\circ \), \( \Delta \alpha = 7.5^\circ \) and \( u_{\text{max}} = 4.56 \text{ mm/min} \).

2.2 Compromise function

The compromise function is defined as the fraction: \( S(g_i) = \frac{V_{\text{cons}(i)}}{V_0} \), where \( V_0 \) is the total sample volume and \( V_{\text{cons}(i)} \) is a volume fraction of all deformed grains (numbered by \( j \)) into which a nucleus \( i \) (with orientation \( g_i \)) can penetrate with some minimum migration rate: \( u_{ij} \geq u_{\text{min}} \). Taking into account that \( V_{\text{cons}(i)} = \sum_j V_j \), the compromise function is finally expressed as:

\[
S(g_i) = \frac{\sum_j V_j}{V_0}
\]

(2)

The value \( u_{\text{min}} = 0.001 \text{ mm/min} \) was used in the calculations.

2.3 Calculation of recrystallization texture

The deformed sample was presented as \( N = 5000 \) grains of the same initial volume with crystal orientation distribution corresponding to the deformation texture. An array of nuclei was generated next with crystal orientations contained in the considered range of the Euler angles space. In the case of sample orthorhombic symmetry (and cubic crystal symmetry) 6859 nuclei were used and they had orientations in the \( 0 \leq \phi_1, \phi_2, \phi_3 \leq \pi/2 \) range. Next, basing on the compromise function, a step function \( c(g) \) is defined, which decides whether a given nucleus with orientation \( g_i \) will grow or not:

\[
c(g_i) = \begin{cases} 1, & \text{if } S(g_i) \geq s_0 \\ 0, & \text{if } S(g_i) < s_0 \end{cases}
\]

(3)

where \( s_0 \) is the assumed level of compromise [12].

It is considered next that a given deformed grain \( j \) can be consumed by many nuclei simultaneously. The following assumption was done: the volume \( \Delta V_{ij} \) of the \( j^{th} \) deformed grain 'consumed' by the \( i^{th} \) nucleus is:

\[
\Delta V_{ij} = \sum_{k=1}^{M} \frac{u_{ij}}{u_{ki}} \cdot V_j
\]

(4)

where \( V_j \) is the initial volume of the \( j^{th} \) grain and the summation on \( k \) is done on \( M \) 'active' nuclei, which fulfil the compromise condition (i.e., for them: \( c(g_k) = 1 \)). And finally, a total volume of the deformed matrix, 'consumed' by the \( i^{th} \) nucleus is:

\[
\Delta V(g_i) = \sum_{j=1}^{N} \Delta V_{ij}
\]

(5)

where \( N \) is the number of grains in the deformed sample. Obviously, it is assumed for non-growing nuclei (\( c(g_i) = 0 \)) that: \( \Delta V(g_i) = 0 \). Finally, the recrystallization texture is calculated as:
where: \( n(g_i) \) is the volume fraction of nuclei with \( g_i \) orientations and \( a \) is a normalization constant.

3. Results

3.1. Recrystallization texture of symmetrically rolled material

The ODF of starting rolling sample of aluminium was represented by 5000 grains of the same volume and corresponding to 50% rolling reduction. It is shown in Fig. 1a. This texture contains copper \((\varphi_1=90^\circ, \phi=35^\circ, \varphi_2=45^\circ)\), brass \((\varphi_1=35^\circ, \phi=45^\circ, \varphi_2=0^\circ)\) and \(S\) \((\varphi_1=59^\circ, \phi=37^\circ, \varphi_2=63^\circ)\) ideal orientations. The compromise function, \(S(g)\), calculated on the basis of this texture, is presented in Fig. 1b. The recrystallization texture (Fig. 1c) was calculated next assuming the compromise threshold \(s_0=0.45\) and it is compared with experimental recrystallization texture of aluminium containing 0.007 % Fe (Fig. 1d) [2]. We observe a very good qualitative agreement between the calculated and experimental recrystallization textures - the same texture maxima appear in the two ODFs being compared. Three ideal orientations are marked in the predicted recrystallization texture (Fig. 1c): the dominating cubic component \((00, 00, 00)\), \(S\) component \((\varphi_1=59^\circ, \phi=37^\circ, \varphi_2=63^\circ)\) and also rotated Goss component \((00, 90^\circ, 45^\circ)\). It should be noted that already the shape of the compromise function shows a very strong similarity with that of the recrystallization texture. Therefore, we conclude that the compromise condition is a very important factor in modelling of recrystallization textures.

3.2. Recrystallization texture of asymmetrically rolled material

The second part of the study was devoted to Al 6061 samples, which were rolled symmetrically and asymmetrically and then annealed at 500 °C during 1 h. The experimentally determined texture of asymmetrically rolled aluminium 6061, where the ratio of angular velocities of the top and bottom identical rolls was equal to 1.1, is shown in Fig. 2a. This texture was presented in \(\varphi_2=0^\circ\) ODF section in the full \(\varphi_1\) range (cf., [13]). This texture was discretized into 5000 grains of the same volume and used next for the calculation of recrystallization texture, which is shown in Fig. 2b. It contains the cubic orientation, which is the sole orientation of the experimental texture of Al 6061 (Fig. 2c). Moreover, the predicted recrystallization texture contains some weaker maxima around the rotated Goss component (this component appears in the recrystallization texture of the Al-0.007 % Fe sample but is absent in that of Al 6061).

It should be added that the experimental recrystallization textures of symmetric and asymmetric rolling of Al 6061 samples are qualitatively the same and they contain only the cubic component (the respective predicted recrystallization textures contain this component as the main one).
Fig. 1. a) Model texture of symmetrically rolled aluminium (reduction 50%, max. intensity: 12), b) calculated compromise function $S(g)$; max. intensity: 0.67, c) predicted recrystallization texture; max. intensity: 11, d) experimental recrystallization texture of rolled Al-0.007% Fe alloy, annealed at 520°C (after [2]). The following texture components are marked: ⬤ copper, ⬤ brass, cubic (■), S (◇), rotated Goss (●). $\varphi_2$=const sections are shown.
Fig. 2. a) Experimental texture of aluminium 6061 rolled asymmetrically (A=1.1.) to 40% reduction (max. intensity: 20), b) predicted recrystallization texture (max. intensity: 28), c) experimental recrystallization texture of asymmetrically rolled aluminium 6061, annealed at 500°C during 1 h (max. intensity: 25). Cubic (◼) and rotated Goss (◇) orientations are shown.

4. Conclusions

The concept of preferred growth, defined by specific misorientations between nuclei and matrix, leads to a correct prediction of the main component of aluminium recrystallization textures (i.e., the cubic orientation) for symmetrically and asymmetrically rolled material. Some differences appear between experimental recrystallization textures of Al - 0.007% Fe and Al 6061 (the first one contains also S and rotated Goss components). The compromise condition was included in our calculations in order to obtain a better prediction of recrystallization textures. The simple approach, used in the presented calculations, leads to relatively good results. This can be explained by the fact that there is principally one preferred misorientation relation in f.c.c. metals (40°<111>), while more complex characteristics of the oriented growth relations are reported for other metals (e.g., for b.c.c. metals).

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