Computational Materials Science 149 (2018) 57–64

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Modelling the evolution of recrystallization texture for a non-grain oriented electrical steel

Hak Hyeon Lee[a], Jaimyun Jung[a], Jae Ik Yoon[a], Jae-Kyoum Kim[b], Hyoung Seop Kim[a,c,*]

[a] *Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea*
[b] *Pohang Research Lab. Steel Products Research Group 2, POSCO, Pohang 37859, Republic of Korea*
[c] *Center for High Entropy Alloys, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea*

ARTICLE INFO

Keywords:
Crystal plasticity
Recrystallization
Finite element method
Electrical steel

ABSTRACT

A new methodology based on the strain energy release maximization (SERM) theory and Avrami-type kinetics is introduced to predict the evolution of recrystallization texture in a non-grain oriented (NGO) electrical steel. The deformation orientation and the activated slip system of each orientation, which can be developed by cold rolling for a hot-rolled NGO electrical steel, were calculated using the finite element method and visco-plastic self-consistent model. Afterwards, the recrystallization orientations that can evolve from each deformation orientation were determined by the SERM theory, and their fraction over the annealing time was calculated based on the Avrami-type kinetic equation. As a result, this approach for the NGO electrical steel could successfully predict the formation of γ-fiber with strong {1 1 1}⟨1 1 2⟩ component during recrystallization, which was in good agreement with the experimental results.

1. Introduction

As a soft magnetic material with a body-centered cubic (BCC) structure, Si steel exhibits easiest magnetization along the ⟨1 0 0⟩ crystal direction. For non-grain oriented (NGO) electrical steels, ⟨1 0 0⟩ directions parallel to sheet surface plane are preferred for superior magnetic properties [1–3]. Unfortunately, conventional rolling process is known to strengthen α-fiber (⟨1 1 0⟩//RD) and γ-fiber (⟨1 1 1⟩//ND), which are unfavorable for the magnetization. In order to transform the crystal orientation developed by cold rolling into texture favorable for the magnetization, recrystallization is essential, but the changes in microstructure and texture during recrystallization are vastly complex and not fully understood. Therefore, in an effort to nurture the easy magnetization direction, the evolution of recrystallization texture for NGO electrical steels is still an ongoing subject of interest.

Because recrystallization texture of a polycrystalline material strongly depends on its processing history [1,2,4–18], diverse processing methods including cold rolling of columnar grains [7–8], α → γ → α phase transformations [9–10], and conventional [12–14] and unconventional rolling schemes [15–18] have been studied to understand the evolution of recrystallization texture for the NGO electrical steel. While these works laid valuable grounds for how specific orientations may nucleate or grow, very few efforts have been made in actually predicting the evolution of recrystallization texture for the NGO electrical steel, which can significantly aid the development of processing methods.

For a model to properly predict the evolution of recrystallization texture, the model should firstly be able to predict what orientations will be formed during recrystallization, and secondly be able to describe the kinetics of recrystallization. While the latter can be handled by employing Avrami-type equation, the former one is often problematic. Currently, most of the theories used to describe the evolution of recrystallization texture are based on oriented nucleation (ON) and oriented growth (OG) theories, but both theories are not quite clear as to which nuclei are preferred given a certain deformation history. This difficulty often becomes an obstacle in predicting the final recrystallization texture because recrystallization texture heavily depends on deformation history.

A suitable theory to correlate deformation mode with stable recrystallization texture is the strain energy release maximization (SERM) theory [19,20]. The theory postulates that a stable recrystallized grain is developed if the grain is oriented in a way such that the strain energy by dislocations in the deformed grain is minimized, or the strain energy release upon recrystallization is maximized. This theory has been successfully utilized in a diverse class of materials such as Al containing high Mn austenitic steels [21], Al and Cu [22], Co thin film [23], low carbon steels [24], and grain-oriented electrical steels [25]. Also, in

---

[*] Corresponding author at: Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea.
E-mail address: hskim@postech.ac.kr (H.S. Kim).

https://doi.org/10.1016/j.commatsci.2018.03.013
Received 10 October 2017; Received in revised form 5 March 2018; Accepted 7 March 2018
0927-0256/

calculating the orientation of the recrystallized grain, the activities of slip systems are used, which means that orientation of the recrystallized grain depends on deformation modes. The fact that the SERM theory accounts for deformation mode is a huge advantage for predicting deformation history dependent recrystallization textures.

In this work, we employed a combined finite element method (FEM) and visco-plastic self-consistent (VPSC) modeling approach to characterize the evolution of deformation texture developed by cold rolling for a hot-rolled NGO electrical steel. Afterwards, the recrystallization orientations that can evolve from each deformed grain were predicted based on the SERM theory, using the slip activities calculated in the combined FEM-VPSC. Finally, the evolution of the recrystallization texture at the specific annealing time and temperature was evaluated using the Avrami-type kinetic equation.

2. Experimental procedure

The NGO electrical steel used in the present work was fabricated by POSCO, containing 2.9 wt% Si. The cold rolling of a hot-rolled steel sheet was subsequently conducted to a final thickness of 0.35 mm. The cold-rolled sheets were isothermally annealed at 750 °C and 830 °C for the various periods of time in Ar atmosphere using a tube-type furnace.

The microstructure and crystallographic texture were measured on the plane perpendicular to the transverse direction (TD) by the electron backscatter diffraction (EBSD) using the field emission scanning electron microscopy (FESEM: XL-30S FEG, Philips Co., Netherlands). The acceleration voltage was 25 kV, and the working distance between the beam and the measured surface was 12 mm. The step sizes used for the measurements varied depending on the magnification and the fraction of the recrystallization. The measured EBSD data, including the orientation distribution functions (ODFs), were treated using the orientation imaging microscopy analysis software (TSL OIM Analysis 7.3, EDAX Inc., USA). Before the analyses, the EBSD data were cleaned up using the grain confidence index (CI) standardization, followed by the single iteration of grain dilation, and the minimum reliable confidence index was set to 0.1. The recrystallized grains were distinguished from the partially-recrystallized specimen using the grain orientation spread (GOS) parameter, and the grains with a GOS value less than 3° were regarded as recrystallized grains.

In order to investigate the kinetics of the recrystallization, the recrystallized fraction for each annealed specimen was experimentally examined using Vickers microhardness tester. Before the hardness test, the specimens were mechanically ground and polished using SiC adhesive paper with the 1200 grit, and the hardness test was carried out under a load of 300 gf and holding time of 10 s. The equation calculating the recrystallized fraction (*f*) can be written as [26]

$$f = \frac{HV_{ini} - HV(t)}{HV_{ini} - HV_{fin}}, \tag{1}$$

where the HV_{ini}, HV_{fin}, and $HV(t)$ represent the recovered hardness value immediately before the recrystallization occurs, the fully-recrystallized hardness value, and the hardness value at annealing time t (min). The moment when the recrystallized fraction is equal to 0% (only recovery) or 100% (full recrystallization) was determined by observing the microstructure in each annealing time via optical microscopy (OM) after chemical etching with the 4% Nital solution.

In order to obtain the hardening curve required for the finite element analysis, uniaxial tensile test on three specimens machined from the hot-rolled sheet was carried out at a strain rate of $1 \times 10^{-3}\,\mathrm{s}^{-1}$ using a universal testing machine (UTM, model 1361, Instron Co., USA). The specimens were dog-bone-shape plate specimens with 5.0 mm gauge length along the rolling direction (RD), 2.5 mm gauge width, and 2.0 mm thickness. In order to evaluate the highly accurate strain, a digital image correlation (DIC) method (ARAMIS 5 M, GOM mbH, Germany) was used in the tensile tests after patterning on a smooth surface without surface roughness.

3. Numerical procedure

3.1. Finite element method

A 2-D finite element simulation for a cold rolling process was conducted with isotropic von Mises yield criterion, using commercial ABAQUS 6.9 software. The roll diameter was designed to be 127 mm, and the initial dimension of a 2-D plane strain matrix representing the electrical steel sheet was set to the length of 80 mm and thickness of 1 mm. The friction coefficient between the roll and matrix was assumed to 0.08, and the lower boundary of the matrix was constrained along the RD due to the symmetric rolling condition. A reduction ratio of 0.35 was achieved so that the extracted velocity gradient history can be repeated four times to reach a final thickness of approximately 0.175. The isotropic hardening model was based on the experimental hardening curve of the hot-rolled NGO electrical steel, and Young's modulus and Poisson's ratio were 190 GPa and 0.3, respectively. The element type of the matrix was a fully-integrated quadrilateral element with 4 nodes (CPE4) and the number of elements was 4000.

Because the VPSC code requires velocity gradient components (L_{ij}) as the input deformation history, a user subroutine UMAT code for ABAQUS 6.9 was written to calculate and extract the components of each element [27,28]. Given a material point in the reference frame $\boldsymbol{X}$ and the material point in the deformed configuration $\boldsymbol{x}$, the deformation gradient tensor $\boldsymbol{F}$ and velocity gradient tensor $\boldsymbol{L}$ are calculated as follows:

$$\boldsymbol{F} = \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{X}}, \tag{2}$$

$$\boldsymbol{L} = \frac{\partial \boldsymbol{v}}{\partial \boldsymbol{x}} = \frac{\partial \boldsymbol{v}}{\partial \boldsymbol{X}}\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{x}} = \dot{\boldsymbol{F}}\boldsymbol{F}^{-1}, \tag{3}$$

$$\dot{\boldsymbol{F}} = \boldsymbol{L}\boldsymbol{F}. \tag{4}$$

If a time increment is given as Δt, the fully implicit time integration of Eq. (4) is

$$\boldsymbol{F}_\tau = \exp(\Delta t \boldsymbol{L}_\tau)\boldsymbol{F}_t \simeq (\boldsymbol{I} + \Delta t \boldsymbol{L}_\tau)\boldsymbol{F}_t, \tag{5}$$

where t, τ, and $\boldsymbol{L}_\tau$ represent the time at the beginning, the time at the end of the time increment, and the velocity gradient at τ, respectively. Then, $\boldsymbol{L}_\tau$ can be expressed as follows:

$$\boldsymbol{L}_\tau = (\boldsymbol{F}_\tau \boldsymbol{F}_t^{-1} - \boldsymbol{I})/\Delta t. \tag{6}$$

3.2. Visco-plastic self-consistent model

In order to predict the texture evolution and calculate the slip activities of individual grains during the cold rolling process, the deformation history from FEM simulation was imported into the VPSC model. In the model, which was originally introduced by Lebensohn and Tomé [29,30], each grain within a polycrystalline aggregate is treated as an anisotropic ellipsoidal inclusion immersed in a homogeneous effective medium (HEM) with average property for the polycrystal. The behavior of a grain is described using the strain-rate sensitivity approach, in which shear rate is defined as

$$\dot{\gamma}^s = \dot{\gamma}_0 \left(\frac{|\boldsymbol{m}^s : \boldsymbol{\sigma}|}{\tau^s}\right)^n sign(\boldsymbol{m}^s : \boldsymbol{\sigma}) \tag{7}$$

$$m_{ij}^s = \frac{1}{2}(b_i^s n_j^s + b_j^s n_i^s). \tag{8}$$

In the above expressions, $\boldsymbol{\sigma}$, $\dot{\gamma}_0$, n, and τ^s represent the grain stress tensor, reference shear strain rate, the inverse of the strain rate sensitivity, and threshold stress for slip, respectively, and the colon indicates double dot product. Also, $\boldsymbol{m}^s$ is the symmetric Schmid tensor of s$^{\text{th}}$ slip