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The evolution of the Goss and Cube textures in electrical steel

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ABSTRACT

The hot-rolled Fe–3%Si alloy sheets with shear deformation textures were cold-rolled by 80% reduction in thickness and annealed at 800 °C. The major components in the hot-rolling textures were {214}⟨121⟩, {113}⟨332⟩, {110}⟨113⟩, and {110}⟨001⟩. The main components in the 80% cold-rolling textures are {111}⟨112⟩ and < 110 > //RD fiber. After the recrystallization, the Goss {110}⟨001⟩ and Cube {010}⟨100⟩ textures strongly developed. According to the calculation of the cold-rolling and recrystallization textures, these components originated from the {110}⟨001⟩ and {110}⟨113⟩ components in the hot-rolling textures. The evolution of the cold-rolling and recrystallization textures was discussed based on the visco-plastic self-consistent (VPSC) deformation model and strain-energy-release-maximization (SERM) model.

1. Introduction

Electrical steel is a soft magnetic material and has high Si contents for reducing the eddy current loss. Grain-oriented electrical steel (GO) has excellent magnetic properties in the rolling direction (RD) and is usually used for the transformer. Because the ⟨100⟩ direction is the easiest magnetization direction in BCC iron, GO must have the strong Goss {110}⟨001⟩ or Cube {010}⟨100⟩ texture. In this study, the evolution of the Goss and Cube textures during the recrystallization (Rex) was investigated. The starting material in experiments was the hot-rolled Fe–3%Si alloy sheet having the shear deformation texture. The evolution of the Rex texture was discussed based on the SERM model which was proposed by Lee [1]. In the model, the Rex texture is determined such that the absolute maximum stress direction (AMSD), which is calculated by slip systems and their activities, is parallel to the minimum Young's modulus direction (MYMD) in recrystallized grains to maximize the strain energy release [1,2].

The measured Rex textures were previously discussed assuming that the deformation behavior is in a stable regime [3]. However, the hot-rolled specimens, which underwent dynamic Rex [3], have a shear texture. Therefore, the deformation behavior may not be in a stable regime. The primary objective of this study is to calculate the cold-rolling texture using the VPSC deformation model and the Rex texture using the SERM model, in which AMSD is calculated from slip systems and their activities are obtained from calculations of the cold-rolling textures.

2. Material and methods

Fe–3%Si alloy sheets, of which the carbon content is 0.002%, were prepared by vacuum induction melting and hot rolling process, in which the preheating and finishing temperatures were 1100 °C and above 900 °C, respectively. The 1 mm-thick hot-rolled sheets, which undergo no phase transformation, were prepared by cutting the surface layer of 5 mm-thick hot-rolled sheets. The shear-textured sheets were cold-rolled by 80% reduction in thickness, which is equivalent to a true thickness strain of 1.61, and annealed for 5 min at 800 °C in Ar atmosphere. The textures of samples, which were cut along the ND–RD sections of the Fe–3%Si alloy sheets, were measured by the EBSD technique. The experimental procedure is described in more detail in Ref. [3].

3. Results and discussion

The texture of the 1 mm-thick hot-rolled sheet is shown in Fig. 1(a). The major components of the hot-rolling texture are {214}⟨121⟩, {113}⟨332⟩, {110}⟨113⟩, and {110}⟨001⟩. The first three components are close to the S {213}⟨364⟩, Copper {112}⟨111⟩, and Brass {110}⟨112⟩ orientations, respectively. These orientations as well as the Goss orientation are known to be obtained in the shear deformation texture of BCC metals [4].

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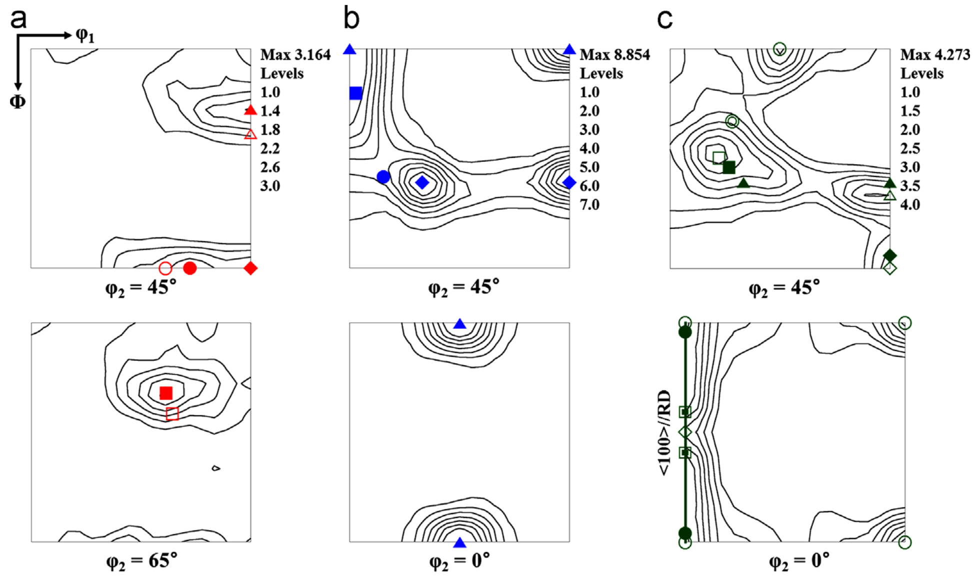

(a) Hot rolling	◆ {110}<001>	● {110}<113> ○ {110}<112>	■ {214}<121> □ {213}<364>	▲ {113}<332> △ {112}<111>
(b) Cold rolling	◆ {111}<112>	● {23 27 24}<314>	■ {6 7 28}<21 22 1>	▲ {001}<110>
(c) Recrystallization	◆ {15 15 2}<1 1 15> ◇ {110}<001>	● {0 15 1}<100> ◎ {225}<17 7 4> ○ {010}<100>	■ {445}<11 6 4> ▣ {034}<100> □ {223}<742>	▲ {111}<112> △ {554}<225>

Fig. 1. (a) Hot-rolling, (b) cold-rolling, and (c) Rex textures of Fe–3%Si alloy sheets, measured by EBSD [3].

Fig. 1(b) and (c) show the 80% cold-rolling and Rex textures. The main components of the cold-rolling texture are {111}⟨112⟩ and < 110 > //RD fiber. The major components of the Rex texture are {223}⟨742⟩, {554}⟨225⟩, {010}⟨100⟩, {110}⟨001⟩, and < 100 > // RD fiber.

In general, the microstructure and texture of hot-rolled Fe–3%Si alloy sheets are not homogeneous through the thickness. The recrystallized grains are formed in the surface layer, whereas the hot band, which is a deformation structure, remains in the center layer, whose texture consists of {112}⟨110⟩ and {001}⟨110⟩ components, from which the texture of cold-rolled sheets inherits [5]. The hot bands in hot-rolled sheets have a great effect on the texture of cold-rolled and recrystallized sheets. Therefore, at high reductions, the ⟨110⟩//RD fiber dominates the texture of the cold-rolled sheet, and the Goss and Cube textures do not develop after Rex.

In order to know where they originate, the cold-rolling textures of (110)[001], (110)[1 −13], (214)[−1 −21], and (113)[−3 −32] oriented crystals representing the main components of {110}⟨001⟩, {110}⟨113⟩, {214}⟨121⟩, and {113}⟨332⟩ in the hot-rolled sheet were calculated using Version 7c of the VPSC code [6]. In the VPSC model, it is assumed that there is no strain hardening and the {110}⟨111⟩ and {112}⟨111⟩ slip systems with the same critical resolved shear stress are activated. The calculated results indicated that the {110}⟨001⟩, {110}⟨113⟩, {214}⟨121⟩, and {113}⟨332⟩ components in the hot-rolling texture were linked to the {111}⟨112⟩, {23 27 24}⟨314⟩, {6 7 28}⟨21 22 1⟩, and {001}⟨110⟩ components in the cold-rolling texture, respectively. The calculated results are in reasonably well agreement with the measured data in Fig. 1(b). The {110}⟨001⟩ to {111}⟨112⟩ change is in agreement with the previous results [7–9].

The evolution of the Rex texture in the cold-rolled sheet was discussed based on the SERM model, and the activity of each slip system is the shear strain $\gamma = \int_0^{e} |d\gamma/d\varepsilon_{11}| d\varepsilon_{11}$ on the slip system, where e is 1.61 [2]. The shear strain rates of active slip systems as a function of strain obtained in the process of calculation of the cold-rolling texture are shown in Fig. 2. The data were used to calculate the Rex texture of the 80% cold-rolled sheet. In the calculation, the slip directions are selected to be at acute angles to RD [2].

The (110)[001] orientation is calculated to rotate to the (11 −1) [112] orientation after 80% cold rolling. The active slip systems are (−1 −1 −2)[−1 −11] and 2.36(11 −2)[111], where the number 2.36 before (11 −2)[111] means that the activity of the (11 −2) [111] system is 2.36 times higher than that of the (−1 −1 −2) [−1 −11] system (Fig. 2-1). It is noted that the active slip directions cannot be summed unlike FCC metals in which all slip directions are related to each other through associated slip planes [2]. However, the active slip directions are on the transverse plane (−110), which is one of slip planes of BCC iron, so they can interact with each other. Thus, the AMSD is [−1 −11]+2.36[111]=[1 1 2.47]. According to the SERM model, this AMSD is parallel to the MYMD ⟨100⟩ of recrystallized grains. Furthermore, in order to minimize the shuffling of atoms during the Rex, the deformed grain and recrystallized grain share the transverse direction (TD) [−110]. Therefore, the Rex orientation is (15 15-2)[1 1 15] (Fig. 3-1), which is similar to the {44 1}⟨118⟩ orientation calculated using the relaxed constraints Taylor model and SERM model [10]. Taking the symmetry into account, the {110}⟨001⟩ orientation in hot-rolling textures is calculated to rotate to the {111} < 112 > deformation orientation and transform into the {15 15 2}⟨1 1 15⟩ ≈ {110}⟨001⟩ Rex orientation.

The (110)[1 −13] orientation, which is close to the Brass component, is calculated to rotate to the (23 27 −24)[314] orientation, which is close to the (11 −1)[314] orientation, after 80% cold rolling. The active slip systems are 1.13(101)[−1 −11], 1.76(01 −1) [111], and (11 −2)[111] (Fig. 2-2). When two active slip systems have the same slip direction, their contributions to AMSD are reduced by 0.5 for BCC metals [2]. Thus, the active slip systems can be divided into two slip systems, 1.13(101)[−1 −11] and 0.88