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Effect of hot band grain size on development of textures and magnetic properties in 2.0% Si non-oriented electrical steel sheet

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ABSTRACT

The effect of hot band grain size on the development of crystallographic texture and magnetic properties in non-oriented electrical steel sheet was studied. After cold rolling the samples with different initial grain sizes displayed different microstructures and micro-textures but nearly identical macro-textures. The homogeneous recrystallized microstructure and micro-texture in the sample having small grains caused normal continuous grain growth. The quite irregular microstructure and micro-texture in the recrystallized sample with large initial grain size provided a preferential growth of grains in ⟨001⟩//ND and ⟨113⟩//ND which were beneficial for developing superior magnetic properties.

1. Introduction

Non-oriented (NO) electrical steels are used in manufacturing of electrical machinery cores, in which high magnetic flux density B and low core loss W are important requirements [1–3]. The magnetic properties of NO electrical steels are influenced by the chemical composition [4,5], sheet thickness [6,7], grain size [8–10] and crystallographic texture [10–12] of the annealed final products [13,14].

With a view to texture, crystalline ferromagnetic materials have an easy magnetization direction which is parallel to the direction of spontaneous domain magnetization in the demagnetized state. In NO electrical steels, domains are spontaneously magnetized to saturation in ⟨100⟩ leading to the easiest direction of ⟨100⟩ for magnetization. The magnetization becomes more difficult in the crystal directions away from ⟨100⟩. Because ⟨111⟩ is farthest from ⟨100⟩ in body centered cubic, ⟨111⟩ become the hardest magnetization direction [1–3].

Because of this magneto-crystalline anisotropy, the magnetic flux density B and core loss W of an NO electrical steel depend on the distribution of orientations g, i.e., the crystallographic texture f (g) of the sheet [15–18]. The orientation g of a grain in a rolled sheet is commonly described by the Miller indices {*hkl*}⟨*uvw*⟩ [19], where {*hkl*} denotes the crystal plane normal parallel to the sheet normal direction (ND) and ⟨*uvw*⟩ is the crystal direction parallel to the rolling direction (RD) of the sample.

Hot bands of NO electrical steel sheets are commonly produced by hot rolling and subsequent hot band annealing. The hot bands are then cold rolled and soft annealed to produce the final products. It has been repeatedly reported that the size of the grains in the hot bands prior to cold rolling affects the texture and magnetic properties of the final products, in that enhanced magnetic properties are obtained from hot bands with large grains [12,13,15,17,20,21]. However, the texture of the hot band also affects the evolution of texture and magnetic properties in the final product, and it is difficult to differentiate the effect of grain size and texture of the hot band on magnetic properties at final gauge.

In this work, two NO electrical steel hot bands with identical random texture yet with distinctly different grain sizes were produced. The two different hot bands were cold rolled and finally annealed in the same manner to produce the final NO electrical steel sheets. Statistical macro-texture quantification was carried out by means of neutron diffraction. The microstructures and micro-textures were analyzed by electron backscattered diffraction (EBSD). The magnetic properties B and W were determined by

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a single-sheet tester. Variations of B and W are discussed by the anisotropy parameter $A(\vec{h})$ which was calculated from the macro-texture results.

2. Experimental procedure

In this study, a hot band of a NO electrical steel containing 2.0% Si was supplied by POSCO; the chemical composition of the steel is listed in Table 1. The as-received hot band with a thickness of 10.0 mm was asymmetrically hot rolled to 2.7 mm thick sheet and then annealed in two different conditions so as to produce two initial samples with identical random texture yet different grain sizes [22,23]. One specimen was annealed at 850 °C for 5 min, whereas the other one was annealed at 1000 °C for 1 h. These two different annealing practices led to different grain sizes of 150 μm and 500 μm as shown in Fig. 1. Hereafter, the two differently annealed sheets are referred to as SG (small grain) and LG (large grain) samples.

Both samples were cold rolled on a reversing laboratory rolling mill with a roll diameter of 127 mm to a final thickness of 0.35 mm, corresponding to a thickness reduction of 87%. Annealing was carried out in argon atmosphere at 700, 800 and 900 °C for 5 min for recrystallization and grain growth.

The conventional X-ray diffraction techniques may hardly provide statistically reliable texture results when the sample has very large grains. Because of the strong penetrating nature of neutrons, neutron diffraction yields macro-texture data representing much larger sample volume of several cubic centimeters [19]. In the present work, macro-textures were determined by measuring three complete pole figures with the help of the four-circle diffractometer (FCD) at the HANARO reactor of Korea Atomic Energy Research Institute, using a neutron beam of wavelength 1.31 Å. The cube-shaped specimens, with size about 10 mm × 10 mm × 10 mm, were prepared by stacking 28 plates cut from the sheets at final gauge [24].

Three-dimensional orientation distribution functions (ODF) $f(g)$ were calculated by the series expansion method according to Bunge ($l_{max.}=22$) [25]. The ODF computations were performed under the assumption of orthotropic sample symmetry, such that $\{0° \le \varphi_1,\ \Phi,\ \varphi_2 \le 90°\}$. Since all relevant orientations and fibers found in the textures of NO electrical steel sheets reside in the $\varphi_2=45°$ section of the Euler space, all ODF representations in this paper are confined to this section [12,19,26]. Fig. 2 shows the positions of ideal orientations and fibers in the $\varphi_2=45°$ section which are often observed in the textures of NO electrical steel sheets.

Microstructures and micro-textures of the cold rolled and subsequently annealed samples were analyzed by electron back-scattered diffraction (EBSD) [19]. The measurements were carried out in a scanning electron microscope equipped with a field-emission gun (FEG). Representation and interpretation of the resulting EBSD orientation maps was performed with the OIM™ analysis system from EDAX Inc.

The magnetic properties at final gauge were measured by a single-sheet tester [10,12,17]. The magnetic flux density B_{50} was determined at a magnetic field strength of $H=5000$ A/m and the core loss $W_{15/50}$ was determined at a magnetic flux density of 1.5 T and 50 Hz. The values of $B_{50}(\alpha)$ and $W_{15/50}(\alpha)$ were measured in intervals $\Delta\alpha$ of 15°, where α is the in-plane angle between the magnetizing direction and the RD of the sample. For this experiment, sheets were cut at seven different directions α and magnetized along their longitudinal direction [10,12].

Table 1
Chemical composition of the non-oriented electrical steel used in this study (rest Fe; in wt%).

Element	Si	Al	Mn	C	N	S
Composition	2.01	0.32	0.21	0.0035	0.0039	0.0022

3. Experimental results

3.1. Development of macro-textures during cold rolling and annealing

The two different hot bands SG (small grain) and LG (large grain) with average grain sizes of 150 μm and 500 μm were cold rolled by 87% and subsequently annealed for 5 min at 700, 800 or 900 °C for recrystallization and further grain growth. Figs. 3 and 4 show the macro-textures determined by neutron diffraction which display the development of cold rolling and annealing textures in the SG and LG samples, respectively.

As shown in Figs. 3(a) and 4(a), quite similar cold rolling textures with only slightly different maximum intensities $f(g)$ developed in the SG and LG samples. The textures consisted of two typical orientation fibers, viz. the ⟨110⟩//RD α-fiber and the ⟨111⟩//ND γ-fiber with similar intensities (see Fig. 2). The maximum of $f(g)$~10 was observed for the orientation {111}⟨110⟩ at (0°, 55°, 45°) where both fibers meet. Thus, the different grain sizes in the hot bands hardly affected the development of cold rolling texture after 87% rolling reduction.

It is noted that the cold rolling textures of the SG and LG samples shown in Figs. 3(a) and 4(a) resemble those of low carbon steel sheets in which the orientations are likewise assembled along the ⟨110⟩//RD and ⟨111⟩//ND fibers [24,27]. As such, the rolling textures of the present samples differ from those commonly observed in NO electrical steel sheets, which display strong ⟨110⟩//RD fiber textures with a maximum at {112}⟨110⟩ as reported elsewhere [10,18].

Whereas the grain size of the hot bands hardly affected the cold rolling textures in the SG and LG samples, it had a significant impact on the evolution of annealing textures. After isochronal annealing at 700, 800 or 900 °C for 5 min, markedly different annealing textures were observed in the SG and LG samples. The orientations in the annealing textures of the SG sample were mostly assembled along the ⟨111⟩//ND fiber with the maximum $f(g)$ at (90°, 55°, 45°) of {111}⟨112⟩ (Fig. 3(b)–(d)). Thus, this material showed no large dependency of annealing textures on annealing temperature, except of a slight increase in texture sharpness upon annealing above 800 °C. Along with the major ⟨111⟩//ND texture in the SG sample, a minor texture component is also observed which comprises orientations residing in the upper left area of the $\varphi_2=45°$ section. With increasing annealing temperature this minor texture component gradually concentrates at (25°, 25°, 45°) close to {113}⟨251⟩.

The annealing textures of the LG sample are given in Fig. 4(b)–(d). Unlike the SG samples, the LG samples displayed a marked change in annealing textures with increasing annealing temperature. The texture of the LG sample annealed at 700 °C consists of orientations along the ⟨111⟩//ND and ⟨001⟩//ND fibers. The maximum $f(g)=6.5$ is found at (30°, 55°, 45°) or {111}⟨112⟩. After annealing at 800 °C, the ⟨111⟩//ND fiber became slightly weaker and orientations along the ⟨001⟩//ND fiber assembled between (20°, 0°, 45°) and (70°, 0°, 45°). In this texture, two maxima with $f(g)=5.4$ and $f(g)=4.4$ were obtained at (30°, 50°, 45°) and (35°, 0°, 45°), respectively. Annealing at 900 °C led to a drastic change in the annealing texture. Orientations along ⟨111⟩//ND nearly vanished, instead orientations with $f(g)=5.0$ along the ⟨001⟩//ND fiber and close to {113}⟨251⟩ dominated the annealing texture.