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Effects of hot rolled microstructure after twin-roll casting on microstructure, texture and magnetic properties of low silicon non-oriented electrical steel

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ABSTRACT

In this work, a 0.71 wt%Si+0.44 wt%Al as-cast strip was produced by novel twin-roll casting. Some as-cast samples were respectively reheated and hot rolled at different temperatures in order to obtain different microstructure prior to cold rolling and annealing. The effects of the hot rolled microstructure on microstructure, texture evolution and magnetic properties were investigated in detail. A coarse deformed microstructure with λ-fiber texture was formed after hot rolling at 850–1050 °C, finally leading to an inhomogeneous recrystallization microstructure with strong λ-fiber, Goss and extremely weak γ-fiber texture. By contrast, a fine transformed microstructure was formed after hot rolling at 1150–1250 °C, finally leading to a fine and homogeneous recrystallization microstructure with stronger α-fiber, γ-fiber and much weaker λ-fiber texture. It should be noted that both the magnetic induction and core loss non-monotonically decreased or increased according to the hot rolling temperature. The unfavorable α-fiber and γ-fiber textures in the annealed sheets were much weaker than those of the conventional products regardless of the hot rolling temperature, thus contributing to a much higher magnetic induction. However, the average grain size in the annealed sheets was much lower than those of the conventional products regardless of the hot rolling temperature, thus leading to a higher core loss except the case of 1050 °C. Hence, it is underscored that better integrated magnetic properties than those of the conventional products can be obtained by optimizing the hot rolled microstructure to produce final desirable recrystallization microstructure and texture.

1. Introduction

Non-oriented electrical steels (NOES) are widely used in the rotating machine cores of motors and generators. Commercial NOES comprise standard material grades as well as high permeability grades, which exhibits larger values of magnetic induction and comparable values of core loss. How to further improve the magnetic properties and reduce the number of processing steps is the timeless topic in both industrial and fundamental research.

The magnetic properties of NOES mainly depend on crystallographic texture, grain size, impurities level, sheet thickness and silicon concentration [1]. It is known that magnetization is hardest in the ⟨111⟩ direction but easiest in the ⟨001⟩ direction of iron crystals. So the λ-fiber texture (⟨001⟩∥ND) with two ⟨001⟩ direction in the rolling plane is most preferable for magnetic induction, and Goss texture ({110}⟨001⟩) with one ⟨001⟩ direction in the rolling plane is also beneficial. By contrast, the γ-fiber texture (⟨111⟩∥ND) with no ⟨001⟩ direction in the rolling plane is most unfavorable. On the other hand, core loss is closely related to the grain size [2]: properly large grain size can decrease hysteresis loss.

However, the columnar structure with strong λ-fiber texture in the initial cast slab is severely destroyed by the heavy hot rolling and cold rolling in the conventional thick (~250 mm) and thin slab (60–90 mm) production routes, and finally leading to strong γ-fiber texture. Therefore, to increase the desirable λ-fiber texture, weaken the deleterious γ-fiber texture and increase the grain size, some additional processing methods such as hot band annealing [1,3,4] or cold rolling in two steps with intermediate annealing [5–8] have to be adopted, and some grain boundary segregation elements such as Sb or Sn [9,10] have to be added in steel. These methods are much in demand in the production of high permeability NOES.

Twin-roll casting technique can directly produce as-cast strips

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with a thickness close to that of the conventional hot rolled strip from the steel melt, and thus offers new possibilities to fabricate steel sheets with a distinct microstructure and properties differing from the conventional products. There is currently significant interest in extending the application of the novel strip casting technology to a wide range of steels. Recently, some trials of strip casting electrical steels have been made successfully [11–13]. Park and Liu et al. reported that large columnar grains with strong λ-fiber texture could be obtained at the initial as-cast strips by controlling the melt superheat [11,14–16], which was desirable to fabricate 3.2%Si and 6.5%Si high permeability grades NOES [17,18]. By contrast, the trials of strip casting low silicon NOES and the investigation on microstructure evolution and magnetic properties have hardly been carried out yet. In particular, the occurrence of $\delta \rightarrow \gamma \rightarrow \alpha$ transformation which is absent in high silicon NOES may play an important role in the microstructure, texture evolution, and magnetic properties of low silicon NOES. Therefore, it is worthwhile clarifying the microstructure, texture development, and the effects of them on magnetic properties of low silicon NOES. In general, one-pass hot rolling with a thickness reduction less than 30% is essential after strip casting, which may modulate the solidified microstructure and texture and thus highly affect the microstructure and texture development at cold rolling and annealing. Hence, how to optimize the hot rolled microstructure and texture so as to obtain final desirable recrystallization microstructure and texture becomes an important issue.

In the present work, a 2.1 mm-thick NOES (0.71 wt% Si+0.44 wt%Al) as-cast strip was produced using a pilot twin-roll strip caster and air cooled to ambient temperature. One-pass hot rolling was done after reheating the strip to different temperatures and followed by cold rolling and annealing. The microstructure and texture along the whole processing route was studied in detail. The focus of this paper has been on clarifying the effects of hot rolled microstructure after strip casting on microstructure, texture evolution and magnetic properties of low silicon non-oriented electrical steel.

2. Experimental procedures

An as-cast strip of low silicon non-oriented electrical steel in the dimensions of 110 mm in width, 2.1 mm in thickness and 11 m in length was produced using a vertical type twin-roll strip caster under a relatively high melt superheat of 70 °C so as to obtain strong columnar structure, and then cooled to room temperature in air, as reported in previous literature [11,15]. The chemical composition of the as-cast NOES strip was Fe–0.006C–0.71Si–0.21Mn–0.44Al (wt%). The equilibrium phase diagram was calculated using Thermo-Calc for the given components. Five strips with a size of 500 L × 110 W × 2.1 T (mm) were cut from the as-cast strip. The strips were respectively reheated up to 850, 950, 1050, 1150, 1250 °C at a rate of about 20 °C/s and held for 2 min in a box furnace, and then respectively hot rolled to a thickness of 1.68 mm in one pass using a laboratory 4-high rolling mill and placed in a box furnace to be held at 650 °C for 1 h to simulate the thermal treatment in the industrial coiling process. After pickling, the hot rolled sheets were cold rolled to a thickness of 0.50 mm and finally annealed at 860 °C for 3 min. In addition, one cold rolled sample with previous hot rolling temperature 950 °C was annealed at 860 °C for 10 s to produce a partially recrystallized microstructure.

Longitudinal sections of samples were mechanical polished and etched with 4% nital for metallographic examination. The mean grain size was determined from optical micrographs by linear intercept method. Samples were also prepared for electron backscattered diffraction (EBSD) scans following standard metallographic techniques involving mechanical polishing and electro-polishing. A solution of 90% ethanol and 10% perchloric acid was used for electro-polishing purpose. EBSD scans were performed on the RD-ND plane of each sample using an OIM 4000 EBSD system equipped on a FEI Quanta 600 Scanning Electron Microscope at 70° tilting condition. The parameters used during scanning were as follows: (1) step size = 2 μm, (2) voltage = 30 kV, (3) work distance = 15 mm. The confidence index was all higher than 90%. A minimum angle misorientation threshold of 10° was set for high-angle boundaries when constructing the orientation image maps. Samples for macro-texture measurement were mechanically polished and etched at room temperature in a solution of 90% H_2O and 10% HCl to relieve the stress. The macro-texture measurement was performed using a Bruker D8 Discover X-ray diffraction with Co $K\alpha_1$ radiation at the center layer of each samples with an area of $20 \times 22\ \text{mm}^2$. The orientation distribution functions (ODFs) were calculated from three incomplete {110}, {200} and {211} pole figures in the range of the polar angle α from 0° to 70° by the series expansion method ($I_{\max}=22$). In case of cubic crystal symmetry and orthorhombic sheet symmetry, an orientation can then be presented by the three Euler angles $0° \leq (\phi_1, \Phi, \phi_2) \leq 90°$. It is thus convenient to depict the ODFs as iso-intensity diagrams in ϕ_2-sections through the Euler space. For better transparency an orientation is presented in terms of the Miller indices {*hkl*}⟨*uvw*⟩, where {*hkl*} describes the crystal plane parallel to ND of the sheet surface and ⟨uvw⟩ the crystal direction parallel to RD. Ferritic steels develop characteristic fiber textures such as λ-fiber (⟨001⟩∥ND), γ-fiber (⟨111⟩∥ND) and α-fiber (⟨110⟩∥RD) and components such as cube ({001}⟨010⟩), rotated cube ({001}⟨110⟩), Goss ({110}⟨001⟩) and rotated Goss ({110}⟨110⟩), as shown in Fig. 1. An quantification of phases was also determined using a Bruker D8 Discover X-ray diffraction (XRD). Magnetic flux density at 5000 A m^{-1} (B_{50}) and core loss at 1.5 T by 50 Hz ($W_{15/50}$) along the rolling direction and along the transverse direction of the annealed samples sheared to 100 mm × 30 mm were respectively measured using a single sheet tester. In addition, the microstructure, texture and magnetic properties of the conventional NOES sheets with the same chemical composition fabricated using the thick slab production route were shown for comparison in the present paper.

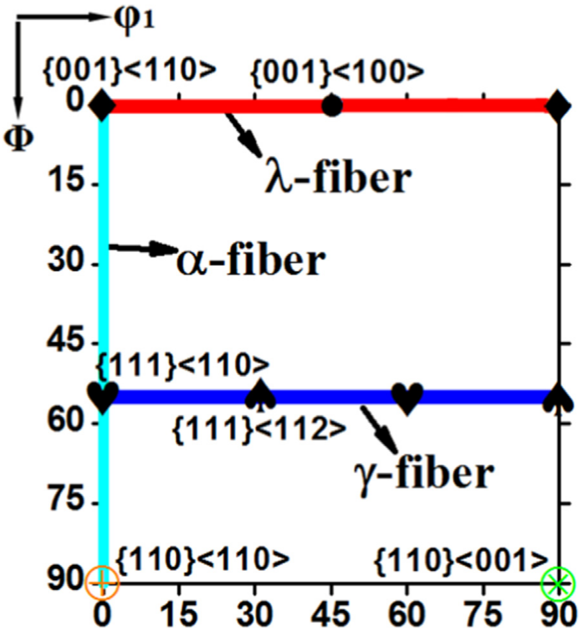

Fig. 1. Typical fiber textures displayed in $\phi_2=45°$ section.