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Effects of initial microstructure and texture on microstructure, texture evolution and magnetic properties of non-oriented electrical steel

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ABSTRACT

An equiaxed grained as-cast strip and a columnar grained as-cast strip was produced by using twin-roll strip casting, respectively. Both as-cast strips mainly containing 0.71 wt%Si and 0.44 wt%Al were cold rolled and annealed with or without the hot rolling prior to cold rolling. Microstructure, texture evolution along the whole processing routes and the magnetic properties were investigated in detail. It was found that the equiaxed grained strip was characterized by almost random texture while the columnar grained strip was dominated by strong λ-fiber (< 001 > ||ND) texture. After cold rolling and annealing, all the final sheets of both the as-cast strips showed extremely weak γ-fiber (< 111 > ||ND) recrystallization texture. In addition, the finally annealed sheets of the equiaxed grained strip were dominated by relatively weak λ-fiber and strong Goss ({110} < 001 >) recrystallization texture while those of the columnar grained strip were dominated by much stronger λ-fiber and much weaker Goss recrystallization texture regardless of whether the hot rolling was adopted before cold rolling, thus the former showed much lower magnetic induction than the latter. On the other hand, even though the finally annealed sheets of the equiaxed grained strip showed a little more homogeneous recrystallization microstructure with a little bigger grain size than those of the columnar grained strip in the case of no hot rolling, a much higher iron loss was displayed. By contrast, in the case of hot rolling, the former exhibited a little lower iron loss than the latter as a result of the more significant increase in grain size and λ-fiber recrystallization texture. The introduction of the hot rolling could increase the grain size, strengthen λ-fiber texture and weaken Goss texture of the finally annealed sheets of both the as-cast strips, leading to a much improvement in both the magnetic induction and iron loss.

1. Introduction

Non-oriented electrical steel (NOES) is a soft magnetic material which is mainly used as core materials of motors and generators. Worldwide, the commercial production lines of NOES are established based on the thick slab (210–250 mm) casting and thin slab (60–90 mm) casting technology. Despite a long history of continuously improved magnetic properties, the further development of NOES is still an exciting field for industrial and joint fundamental research. The driving force for research and development are on the one hand increasing quality demands, i.e. still lower losses and higher permeability for more energy-efficient and miniaturized motors, and on the other hand the pressure to reduce manufacturing costs in order to stay competitive on the market.

The novel near-net-shape strip casting can directly produce as-cast strips from the steel melt with a thickness of 1–3 mm close to that of the conventional hot rolled strips by omitting multi-pass hot rolling on the one hand and show a very high solidification rate on the other hand. In the past two decades, there was a significant interest in extending the potential application of strip casting technology to electrical steels [1–3]. Some trials of strip casting grain-oriented electrical steels [4–6] and NOES [7–10] have been made successfully and some work has been carried out to study the evolution of microstructure and texture at different processing steps [4–10]. Park and Liu et al. reported that the initial as-cast microstructure could be effectively controlled by changing the melt superheat [8,11–13]. As a result of the initial small thickness and subsequent very limited rolling reduction, the different initial as-cast microstructure and texture may greatly

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impact the microstructure and texture evolution of NOES at rolling and annealing. However, these influences have not been understood yet. Therefore, it is worthwhile clarifying the effects of initial solidification structure and texture on the microstructure, texture evolution and magnetic properties of NOES to be an effort to optimize the NOES production route based on strip casting technique.

In the present work, an as-cast strip with equiaxed grained structure and an as-cast strip with columnar grained structure was respectively produced by using a pilot twin-roll strip caster. Both as-cast strips mainly contained 0.71 wt%Si+0.44 wt%Al. Both as-cast strips were treated by one processing route (direct cold rolling and annealing) and the other processing route (hot rolling, cold rolling and annealing). The microstructure, texture evolution along the whole processing routes was characterized in detail. The focus was on uncovering the effects of the initial solidification structure and texture on through process microstructure, texture evolution and final magnetic properties.

2. Experimental procedures

A 1.35 mm-thick as-cast strip and a 2.1 mm-thick as-cast strip were produced by using a vertical type twin-roll strip caster with a roll gap of 1.3 mm and 2.05 mm, respectively, as reported in previous literature [11,12]. Both the as-cast strips were cooled to room temperature in air. The chemical composition of the as-cast strips was Fe–0.006C–0.71Si–0.21Mn–0.44Al (in wt%). The equilibrium phase transformation temperatures were calculated by Thermo-Calc for the given components. '$L \rightarrow L = \delta \rightarrow \delta \rightarrow \delta + \gamma \rightarrow \gamma \rightarrow \gamma + \alpha \rightarrow \alpha$' transformation process occurs in sequence as the temperature decreases. The $\delta+\gamma$ and $\gamma+\alpha$ ranges are respectively 1277–1308 °C and 1023–1099 °C.

Sheets in the size of 500mm (L) × 110 mm (W) were respectively cut from the 1.35 mm-thick strip and 2.1 mm-thick strip. Different processing routes including rolling and annealing were carried out as follows:

(1) One 1.35 mm-thick as-cast sheet was cold rolled to 0.50 mm and finally annealed at 860 °C for 3 min. The samples at different processing steps were denoted as cast sheet (I-CS), cold rolled sheet (I-CR) and cold rolled & annealed sheet (I-CR&A).
(2) One 1.35 mm-thick as-cast sheet was reheated up to 950 °C at a rate of about 20 °C/s and held for 2 min, hot rolled to 1.08 mm in one pass and then immediately placed in a box furnace to hold for 1 h at 650 °C. Then the hot rolled sheet was cold rolled to 0.50 mm and finally annealed at 860 °C for 3 min. The samples at different processing steps were denoted as hot rolled sheet (II-HR), cold rolled sheet (II-HR&CR) and cold rolled & annealed sheet (II-HR&CR&A).
(3) One 2.1 mm-thick as-cast sheet was cold rolled to 0.50 mm and finally annealed at 860 °C for 3 min. The samples at different processing steps were denoted as cast sheet (III-CS), cold rolled sheet (III-CR) and cold rolled & annealed sheet (III-CR&A).
(4) One 2.1 mm-thick as-cast sheet was reheated up to 950 °C at a rate of about 20 °C/s and held for 2 min, and hot rolled to 1.68 mm in one pass and then immediately placed in a box furnace to hold for 1 h at 650 °C. Then the hot rolled sheet was cold rolled to 0.50 mm and finally annealed at 860 °C for 3 min. The samples at different processing steps were denoted as hot rolled sheet (IV-HR), cold rolled sheet (IV-HR&CR) and cold rolled & annealed sheet (IV-HR&CR&A).

The microstructure on longitudinal sections as defined by the rolling direction (RD) and the normal direction (ND) was characterized by both the metallographic investigation and orientation image maps (OIM). The mean grain size was determined from optical micrographs by linear intercept method. The OIM was measured by using an OIM 4000 Electron backscattered diffraction (EBSD) system equipped on a FEI Quanta 600 scanning electron microscopy with a step length of 0.5 μm. The macro-texture on the mid-thickness layer of different samples was measured by using a Bruker D8 Discover X-ray diffraction with Co $K\alpha_1$ radiation. Then the orientation distribution functions (ODFs) were calculated using the series expansion method ($l_{max}=22$) from the obtained three incomplete pole figures {110}, {200} and {211} with the polar angle α from 0° to 70°. In case of cubic crystal symmetry and orthorhombic sheet symmetry, an orientation can be presented by the three Euler angles $0° \le (\varphi_1, \Phi, \varphi_2) \le 90°$. For better transparency an orientation is presented in terms of the Miller indices {*hkl*}<*uvw*>, where {hkl} describes the crystal plane parallel to ND and <uvw> describes the crystal direction parallel to RD. Some characteristic fiber textures such as λ-fiber (<001>||ND), γ-fiber (<111>||ND) and α-fiber (<110>||RD) and some important components such as cube ({001}<010>), rotated cube ({001}<110>), Goss ({110}<001>) and rotated Goss ({110}<110>) were focused on in the present work. Samples in the size of 100 mm (L) × 30 mm (W) were cut from the finally annealed sheets respectively along RD and TD for measuring magnetic properties using a single sheet tester. The magnetic properties including the magnetic induction at 5000 A m^{-1} (B_{50}) and the iron loss at 1.5 T and 50 Hz ($W_{15/50}$) were obtained.

3. Results

3.1. Characterization of the microstructure and texture of the initial as-cast strips

Fig. 1 shows the optical microstructure, orientation image maps and texture of the initial as-cast strips. It was somewhat difficult to give an exact quantitative estimation of the average grain size and texture because the as-cast grains were very large. The scanned area affected the results to some extent. In the present work, the scanning areas were 1.35 mm (ND) by 10 mm (RD) and 2.1 mm (ND) by 10 mm (RD) for the 1.35 mm-thick and 2.1 mm-thick as-cast strips, respectively. It can be seen that the microstructure of the 1.35 mm-thick as-cast strip was dominated by large equiaxed grains with a size range of 300 to 600 μm and a few tiny grains, as shown in Fig. 1a and b. The texture was characterized by almost random texture except a mild component close to {001}<210> (Fig. 1c). By contrast, the microstructure of the 2.1 mm-thick as-cast strip was dominated by large columnar grains with a diameter range of 80–300 μm (Fig. 1d and e). Some small irregularly-shaped grains were also observed. The texture of the 2.1 mm-thick as-cast strip was characterized by strong λ-fiber texture (Fig. 1f).

3.2. Characterization of the microstructure and texture in the processing route without hot rolling prior to cold rolling

Fig. 2 shows the directly cold rolled microstructure and the finally annealed microstructure of both the equiaxed grained strip and columnar grained strip. A coarse and inhomogeneous deformed microstructure was produced in the cold rolled sheet of the equiaxed grained strip. Lots of in-grain shear bands were displayed with an inclination angle of 20–30° with respect to the RD. The area fraction of the deformed grains with in-grain shear bands was (38 ± 5)%. After annealing, an inhomogeneous recrystallization microstructure with an average grain size of 25.5 μm was obtained. By comparison, a more inhomogeneous deformed microstructure was formed in the cold rolled sheet of