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High-permeability and thin-gauge non-oriented electrical steel through twin-roll strip casting

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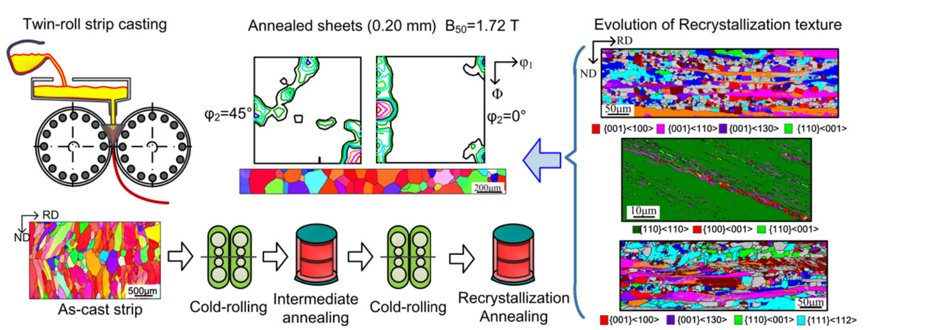
HIGHLIGHTS

- 0.2-mm-thick non-oriented electrical steels with high-permeability were successfully fabricated by strip casting.
- As-cast {100} texture can be partially retained even though for a deformation with reduction up to 91%.
- New Goss and Cube substructures were formed in the deformed {110} ⟨110⟩ grains.
- Annealed sheets processed by one-stage rolling exhibited strong {111} ⟨112⟩, {223} ⟨110⟩ and weak Goss and Cube textures.
- High magnetic induction B_{50} of 1.72 T with strong Cube and Goss texture was obtained by two-stage rolling.

GRAPHICAL ABSTRACT



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ABSTRACT

Texture optimization has always been a challenge to fabricate non-oriented electrical steels (NOES). In the present study, thin-gauge NOES with high permeability was successfully processed using an innovative and convenient twin-roll strip casting process without hot rolling. The relation between the as-cast microstructure, processing route and texture evolution was studied. The results indicated that as-cast strip with coarse grains exhibited strong {100} ⟨0vw⟩ texture and unique {110} ⟨110⟩ component. Annealed sheets processed by one-stage rolling displayed pronounced {111} ⟨112⟩, {223} ⟨110⟩ components and weak Cube and Goss texture. Micro-texture characteristics revealed that {100} ⟨0vw⟩ texture was partially retained from initial grains, and new Cube and Goss substructures were generated within {110} ⟨110⟩ deformed grains during cold rolling. This was responsible for the development of Cube and Goss recrystallization texture. Furthermore, the application of two-stage rolling not only reinforced these two behavior, but also accelerated the nucleation of η grains because of the increased shear bands in cold-rolled sheets. In this manner, an improved texture consisting of dominant η-fiber, weak γ-fiber and optimized magnetic properties (B_{50} = 1.72 T, $P_{10/400}$ = 14.91 W/kg) were obtained.

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1. Introduction

As important soft magnetic materials, non-oriented electrical steels (NOES) are widely used to manufacture cores for motors and engines. With the rapid development of frequency conversion technology, higher requirements for magnetic performance including magnetic induction and core loss have been proposed [1,2]. The NOES in traction motors of electric vehicles (EV) and hybrid electric vehicles (HEV), for example, not only require low core loss (particularly at medium and high frequencies) to improve the motor efficiency, but also need high magnetic induction to enhance motor torque [3,4]. In terms of core loss, the classical eddy current loss, which is proportional to the square of the thickness of final sheets, is the dominant part at high frequency [5]. Hence, an effective method to decrease the core loss is to reduce the thickness of the electrical steel, resulting in significant increase in the demand for NOES with thickness of 0.30 mm or less [6]. In the fabrication of thin-gauge product, texture control is a technical difficulty besides controlling flatness and stress monitoring [1–8]. It is well known that the decrease in thickness, i.e. increase in cold rolling reduction, enhances the harmful γ (〈111〉 //ND) recrystallization texture and sharply deteriorates the permeability. Therefore, one focus of research on thin-gauge NOES with high-quality is to improve the recrystallization texture, in order to solve the compatibility of low core loss and high magnetic induction.

In conventional processing routes, including thin-slab continuous-casting and hot rolling, the effects of alloying elements, rolling methods and heat treatment on recrystallization texture have been studied to optimize permeability. Tanaka et al. [9,10] reported that phosphorus segregation at grain boundaries suppressed the nucleation of detrimental {111} 〈112〉 grains. Zhang et al. [11] obtained a strong {100} 〈0vw〉 and {hk0} 〈001〉 texture taking advantage of columnar-grained cast slabs containing carbon and MnS inhibitor. Huang et al. [12] studied the effect of cold rolling process on texture, and observed that the introduction of transverse rolling could enhance {100} 〈001〉 texture. Although these methods significantly improve the recrystallization texture of products, some of them are very difficult for industrial application because of the high production cost or complicated process. Therefore, other effective and convenient techniques have to be explored.

Twin-roll strip casting (TRSC) is one advanced near net shape casting technique, in which molten steel can be directly solidified into as-cast strip with thickness of 1–5 mm, leading to a drastic simplification of processing operation [13–15]. TRSC is suitable for the preparation of numerous thin steel products [16–18], and its application in manufacturing electrical steels has been investigated in recent years. Liu et al. [19,20] not only studied the formation mechanism of solidification structure and texture of strip-cast silicon steel, but also reported the texture evolution and magnetic properties. Sha et al. [21] and Xu et al. [22] revealed the origin of Cube {001} 〈100〉 texture in strip-cast electrical steels. Moreover, Zu et al. [23] and Li et al. [24] studied the evolution of microstructure and texture in strip cast 4.5 wt% Si and 6.5 wt% Si electrical steel, respectively. Although these studies provided a better understanding of the physical metallurgy of strip-cast electrical steels, the study on microstructure and texture evolution of thin-gauge NOES has been ignored.

In the present study, thin-gauge 3.0% Si non-oriented electrical steel of 0.20 mm thickness was produced by twin-roll strip casting, and different cold rolling processes were designed and adopted. The subject of the study described here is to elucidate the evolution of microstructure and texture at various stages and optimize final magnetic properties.

2. Experimental procedure

The non-oriented as-cast strip of 2.1 mm thickness and containing 0.004% C, 3.0% Si, 0.2% Al, 0.1% Mn, 0.005% N, 0.005% S, 0.004% P, was processed by a vertical type twin-roll strip caster [22]. Copper rollers were used for experiments, and the melt superheat of molten steel was set to 40 °C. Fig. 1 shows a schematic diagram of processing routes. Samples cut from the as-cast strip were cold rolled to 0.2 mm via one-stage process and two-stage process, respectively. One-stage process implies that the as-cast strip was directly cold rolled to 0.2 mm in eight rolling passes (total ~ 91% reduction) and is referred as Route 1. Two-stage process was carried out involving first cold rolling reduction of 67% (to ~0.70 mm in four rolling passes), 76% (to ~0.50 mm in five rolling passes) and 83% (to ~0.35 mm in six rolling passes), which are respectively referred as Route 2, Route 3 and Route 4. Additionally, the first cold-rolled sheets were subjected to intermediate annealing at 1030 °C for 3 min. Subsequently, all the cold-rolled sheets with 0.20 mm thickness were subjected to recrystallization annealing at 1000 °C for 5 min under N_2 atmosphere.

Optical microscopy (OM) and OIM 4000 EBSD (electron backscatter diffraction, HKL Channel 5) system equipped at FEI Quanta 600 SEM (scanning electron microscopy) were used to characterize the microstructure. Samples were mechanical polished and etched by 4% nital solution for OM while electropolished with a 13% perchloric acid/alcohol solution for EBSD. For macro-texture analysis, samples of 22 mm (RD) × 20 mm (TD) were prepared. Three incomplete pole figures {200}, {110} and {211} with polar angle α from 0° to 75° at voltage of 35 kV were measured using Bruker D8 Discover X-ray diffraction with CoKα1 radiation. The ODFs (orientation distribution functions) were calculated by TexTools software and series expansion method ($I_{max} = 22$) based on the XRD data. The volume fraction of major texture components was also carried out by the software from the XRD data. In addition, the micro-texture was analyzed by EBSD system, and the corresponding ODFs were computed using Salsa software. In the case of orthorhombic sheets and cubic crystal symmetry, an orientation can be indicated by three Euler

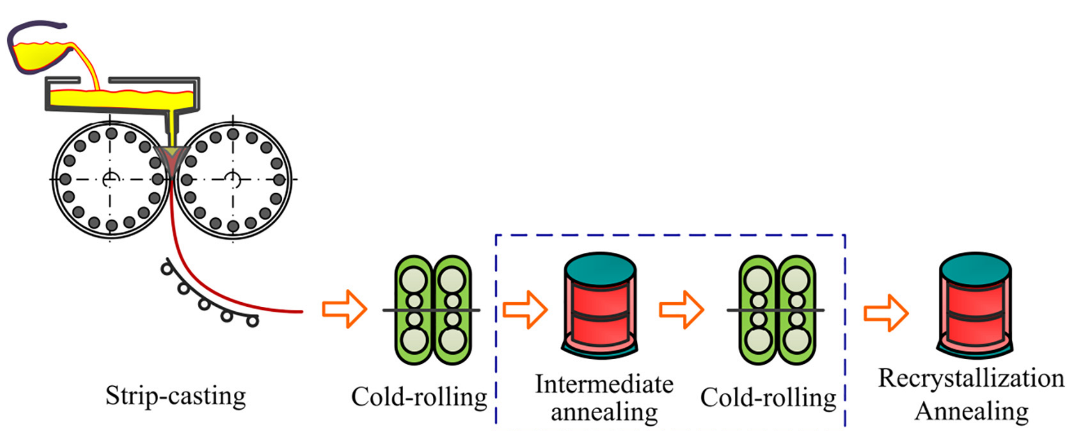

Fig. 1. Schematic diagram of processing routes.