Journal of Materials Science & Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Significant effect of as-cast microstructure on texture evolution and magnetic properties of strip cast non-oriented silicon steel

Haitao Jiao[a,*], Yunbo Xu[a,*], Wenzheng Qiu[a], Haijie Xu[a], R.D.K. Misra[b], Yifeng Du[c], Jianping Li[a], Guodong Wang[a]

[a] *State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China*
[b] *Laboratory for Excellence in Advanced steel Research, Department of Metallurgical, Materials, and Biomedical Engineering, University of Texas at El Paso, TX 79968, USA*
[c] *Liaoyang Petroleum Steel Pipe Manufacturing Company, Liaoyang 111003, China*

ARTICLE INFO

Article history:
Received 27 January 2018
Received in revised form 30 March 2018
Accepted 27 April 2018
Available online xxx

Keywords:
As-cast microstructure
Non-oriented silicon steel
Strip casting
Texture
Magnetic properties

ABSTRACT

In this study, two types of as-cast microstructure produced by strip casting were cold rolled and annealed to investigate the effect of initial microstructure on the textural evolution and magnetic properties of non-oriented silicon steel. The results indicated that the cold-rolled sheets of coarse-grained strip with pronounced {100} components exhibited stronger λ fiber ($\langle 100\rangle$//ND) and weaker γ fiber ($\langle 111\rangle$//ND) texture as composed to the fine-grained strip with strong Goss ($\{110\}\langle 001\rangle$) texture. After annealing, the former was dominated by η fiber ($\langle 001\rangle$//RD) texture with a peak at $\{110\}\langle 001\rangle$ orientation, while the latter consisted of strong $\{111\}\langle 112\rangle$ and relatively weak $\{110\}\langle 001\rangle$ texture. In addition, a number of precipitates of size ~30–150 nm restricted the grain growth during annealing, resulting in recrystallization of grain size of ~46 μm in the coarse-grained specimen and ~41 μm in the fine-grained specimen. Ultimately, higher magnetic induction (~1.72 T) and lower core loss (~4.04 W/kg) were obtained in the final annealed sheets of coarse-grained strip with strong {100} texture.

1. Introduction

Non-oriented silicon steel is the most important soft magnetic material used as a core material in electric motors and generators [1]. It generally requires high magnetic induction and low core loss to reduce the energy loss and enhance the energy conversion during the operation of equipment. The key to achieving superior magnetic properties is optimizing the texture and microstructure of the product. In BCC silicon steel, {100}<0*vw*> orientation is the desired texture because $\langle 001\rangle$ is the easy magnetization direction [2]. In addition, there is an optimum grain size for the minimal core loss in a specific Fe-Si alloy [3]. During conventional processing, heavy hot rolling leads to strong α ($\langle 110\rangle$//RD) and γ ($\langle 111\rangle$//ND) oriented microstructure in the hot band and is inherited in the cold-rolled sheet [4]. This kind of microstructure and texture gives rise to pronounced γ and α^* ({11 h}<1, 2, 1/h>) recrystallization texture [4], resulting in poor permeability and limiting the improvement of magnetic properties of non-oriented silicon steel. In recent years, twin-roll strip casting was employed to fabricate non-oriented silicon steel. As the new generation "near-net shape" casting process, strip casting can provide strip with thickness of 1–5 mm directly from the molten steel [5,6]. It significantly diminishes the hot rolling process and reduces the deformation of the as-cast microstructure. Studies have indicated that strip casting has obvious advantage, such as energy efficiency and high permeability, in fabricating non-oriented silicon steels [7–10].

Recrystallization texture and magnetic properties of non-oriented silicon steel significantly depend on the microstructure and texture prior to cold rolling. The microstructure of conventional hot bands of non-oriented silicon steel is composed of equiaxed grains in the surface layer and elongated grains in the mid-thickness layer [11]. Lee et al. [12] reported that the hot bands with large initial grain size favored the preferential growth of new {100} and {113} oriented grains, which were beneficial for developing high magnetic flux density and low core loss. Thus, the hot band annealing process is commonly performed to increase the grain size in the hot rolled bands. As for the twin-roll strip casting process, the as-cast strips are directly used as material for

---

* Corresponding authors.
E-mail addresses: andrewjiao@163.com (H. Jiao), yunbo_xu@126.com (Y. Xu).

https://doi.org/10.1016/j.jmst.2018.05.007
1005-0302/

Table 1
Chemical composition (wt%) and casting parameters of as-cast strips.

Material	C	Si	Al	Mn	S	N	Superheat (°C)	Casting speed (m/min)
A	0.004	3.0	0.48	0.25	0.0044	0.0052	50	24
B	0.004	2.9	0.52	0.61	0.0056	0.0035	35	20

cold rolling. As previously reported [13], the microstructure of as-cast strip was difficult to adjust by annealing process unless the temperature was higher than 1100 °C. However, Park et al. [14] reported that various microstructures of as-cast strip can be directly obtained by changing the casting parameters. Therefore, revealing the relationship between as-cast microstructure and texture evolution is important to optimize the casting process and improve the magnetic properties.

In this work, two as-cast strips with different microstructure and texture were produced by strip casting, and subsequently cold rolled and annealed. The aim of this study is to elucidate the effect of initial microstructure on the texture evolution and the magnetic properties of strip cast non-oriented silicon steels.

2. Materials and experimental procedure

Two 2.4 mm-thick non-oriented silicon steel strips used in this study were prepared by twin roll strip caster with 220 mm-width casting rolls [10]. The strips were air cooled to room temperature after casting. Chemical composition and casting parameters of steels A and B are listed in Table 1. According to the thermodynamic calculations, the microstructure of these two materials was ferrite at temperatures below the melting point, i.e. no phase transformation occurred during casting. In addition, the slight increase (~0.36%) of Mn in material B was to improve {100} recrystallization texture and magnetic properties [15]. After pickling in 15% hydrochloric acid solution, the strips were directly cold rolled to 0.50 mm and finally annealed at 950 °C for 5 min in the N_2 atmosphere. In addition, some cold rolled samples were annealed at temperatures between 650 °C and 800 °C in order to observe the development of recrystallized microstructure.

Samples cut from the cold rolled sheets and the annealed samples were mechanically polished and etched by 4% nital for microstructure analysis by means of optical microscope. The grain size of samples was measured by using the standard intercept method under optical metallography, while the recrystallization fraction was calculated by image analysis. The micro-orientation and grain boundaries of grains in as-cast strips and some recrystallized samples were characterized by electron backscattered diffraction system (EBSD) equipped at FEI Quanta 600 scanning electron microscopy (SEM). Prior to EBSD observation, the samples were electropolished in a 13% perchloric acid/alcohol solution at an applied voltage of 26 V for 22 s. The measured data from EBSD were post-processed with the Channel software. In addition, the samples with an area of 18 nn × 22 mm were mechanically polished and etched in 10% hydrochloric acid solution to relieve the stress for macro-texture analysis. The macro-textures were determined using Bruker D8 Discover X-ray diffraction. Orientation distribution functions (ODF) were calculated from {200}, {110} and {211} incomplete pole-figures and by the series expansion method ($L_{max} = 22$). The precipitates were investigated using Tecnai G2 transmission electron microscope (TEM) equipped with an energy dispersive spectrometer (EDS). For the TEM analysis, the samples were mechanically thinned to ~ 50 μm and then electropolished in 13% perchloric acid and 87% ethanol solution at a voltage of 32 V at −25 °C. The magnetic induction at 5000 A/m (B_{50}) and the core loss at 1.5 T and 50 Hz ($P_{15/50}$) were measured using a single sheet tester both in the rolling direction (RD) and transverse direction (TD) of the as sheared 100 mm × 30 mm annealed sheets.

3. Results and discussion

3.1. Microstructure and texture of as-cast strip

Fig. 1 shows the microstructure of as-cast strip A and strip B, where the EBSD step size was 2.50 μm. The average grain size obtained using the intercept method was about 340 ± 8 μm and 210 ± 5 μm, respectively. Sample A exhibited primarily columnar grains where the length direction displayed a deviation angle of 10°–30° from the ND (normal direction) of strip (Fig. 1(a)). More-

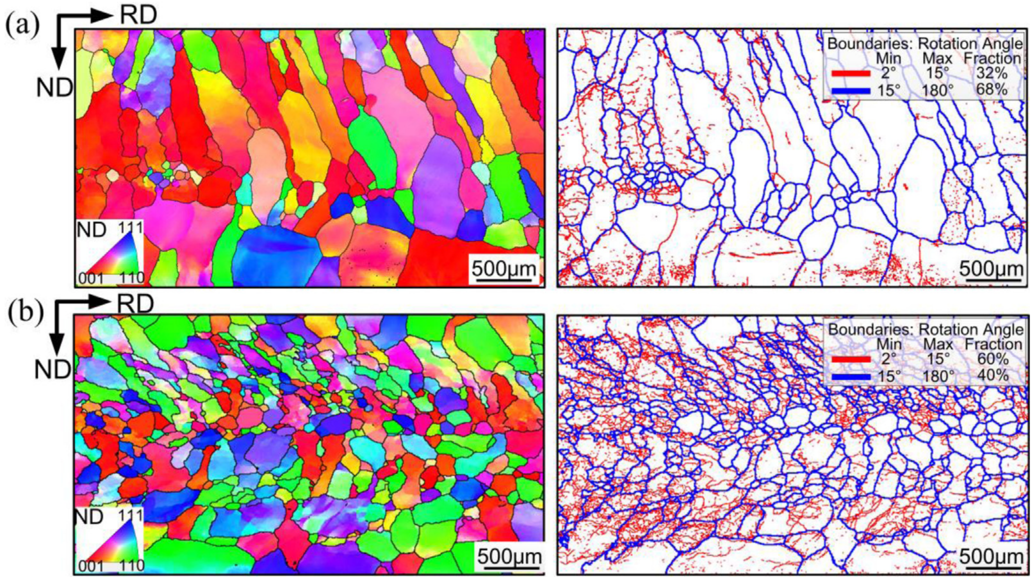

Fig. 1. Orientation image maps and the corresponding grain-boundary maps of (a) as-cast strip A and (b) as-cast strip B.

Please cite this article in press as: H. Jiao, et al., J. Mater. Sci. Technol. (2018), https://doi.org/10.1016/j.jmst.2018.05.007