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Fabrication of grain-oriented silicon steel by a novel way: Strip casting process

Hong-Yu Song, Hai-Tao Liu*, Hui-Hu Lu, Ling-Zi An, Bao-Guang Zhang, Wen-Qiang Liu, Guang-Ming Cao, Cheng-Gang Li, Zhen-Yu Liu, Guo-Dong Wang

State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, PR China

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ABSTRACT

A 0.23 mm-thick grain-oriented silicon steel sheet was successfully produced by a new process including strip casting, hot rolling, normalizing, two-stage cold rolling with an intermediate annealing, primary annealing and secondary recrystallization annealing. Microstructure, texture and inhibitor evolutions were briefly investigated. It was shown that Goss texture was absent in the hot rolled strip. After normalizing, a number of finely dispersed MnS precipitates with a diameter of 20–80 nm were formed. The primary annealed strip exhibited fully recrystallized microstructure with the average grain size of 13 μm, together with weak α-fiber and relatively strong and uniform γ-fiber texture. However, the Goss texture was not observed, which was significantly different from previous results that the Goss texture was the most populous component in the primary recrystallization texture of two-stage route. After secondary recrystallization annealing, very large grains with a grain size of 6–40 mm were formed and the magnetic induction B_8 was as high as 1.84 T.

1. Introduction

Twin-roll strip casting is based on the concept originally proposed by Bessemer, in which 1–5 mm thick strips can be produced directly from the molten metal [1]. It is characterized by a significantly high heat extraction capacity [2]. Metallurgists have made lots of efforts to apply strip casting in the manufacturing of steels due to its superiority over conventional process [3–5]. Recently, Liu et al. [6–9] successfully produced high-permeability non-oriented silicon steel based on strip casting by sufficiently utilizing its advantage in controlling the solidification texture. It is reported that the ideal texture for use in electrical motors is found in the section transverse to the columnar growth direction of ferritic steels solidification [10]. Liu et al. [6] found that this desired texture could be achieved by controlling key technological parameters during strip casting. Thus, strip casting has a great advantage in manufacturing non-oriented silicon steels.

Grain-oriented silicon steel is an ideal core material for transformers due to its excellent magnetic properties originating from the sharp {1 1 0}⟨0 0 1⟩ orientation (Goss texture) [11]. It can be classified into two grades according to the properties, i.e. conventional grade (CGO) and high permeability grade (Hi-B) [12]. In the manufacturing, two essential requirements must be met, i.e. a fine dispersion of inhibitors and a suitable structure of primary recrystallized grains [13]. It is known that finely dispersed inhibitors can induce secondary recrystallization by blocking the growth of matrix grains, and Goss texture originated during hot rolling has an important influence on the nucleation of {1 1 0}⟨0 0 1⟩ secondary grains [14,15]. In conventional process, the slabs or ingots are usually reheated over 1350 °C to dissolve coarse precipitates formed earlier, and the desirable inhibitors are re-precipitated during multi-pass hot rolling and normalizing. Goss texture is originated due to severe shear deformation during hot rolling in which the reduction usually exceeds 90% [16]. By contrast, the inhibitor precipitation may be significantly suppressed during strip casting due to the high cooling rate. Thus, strip casting has a great potential advantage in controlling the inhibitor precipitation without high-temperature reheating. However, given that the thickness of as-cast strips is close to that of hot rolled strips, MnS precipitation may be limited due to few hot rolling passes and the origination of Goss texture may be also restricted due to lack of shear deformation. Consequently, microstructure, texture and inhibitor evolutions of strip-cast grain-oriented silicon steel may be significantly distinct from those in conventional process. However, the corresponding investigations have not yet been reported.

For this aim, a 0.23 mm-thick grain-oriented silicon steel sheet was evaluated based on a new process including strip casting, hot rolling, normalizing, two-stage cold rolling with an intermediate annealing, primary annealing and secondary recrystallization

* Corresponding author. Tel.: +86 24 83686739; fax: +86 24 23906472.
E-mail address: liuht@ral.neu.edu.cn (H.-T. Liu).

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annealing. Microstructure, texture and inhibitor evolutions were briefly investigated.

2. Experimental

The composition of tested steel was (wt%) 0.057C, 3.31 Si, 0.090 Mn, 0.026 S, and balance Fe. The 3.6 mm-thick as-cast strip was produced by using strip casting, as reported in previous literatures [17,18]. The as-cast strip was hot rolled to 2.3 mm at 1130 °C, cooled by cold water and followed by normalizing in which the hot rolled strip was respectively soaked at 1130 °C and 930 °C for 2 min and quenched by boiling water. The normalized strip was cold rolled to 0.8 mm, followed by intermediate annealing at 830 °C for 5 min and second cold rolling to 0.23 mm. The cold rolled strip was then annealed at 830 °C for 5 min in a wet atmosphere of 75% H_2 and 25% N_2. Finally, the strip was heated to 1200 °C from 800 °C at 15 °C/h in an atmosphere of 75% H_2 and 25% N_2 and then annealed at 1200 °C for 20 h in 100% H_2.

The orientation distribution functions (ODFs) of the specimens were measured and calculated based on X-ray diffraction. The measured layer is defined as the parameter $S=2a/d$, where a and d are the distances from the center and sheet thickness, respectively. Electron backscattered diffraction (EBSD) analysis was also performed. Optical microscopy and EBSD were applied on longitudinal sections as defined by the rolling direction (RD) and the normal direction (ND). The observation of precipitates was conducted in a transmission electron microscope equipped with an energy dispersive X-ray spectroscopy. The magnetic induction at 800 A/m (B_8) was measured by using a single sheet tester in the rolling direction of as sheared 100 mm × 30 mm samples.

3. Results and discussion

The as-cast strip was composed of coarse columnar ferrite grains and martensite (Fig. 1a), and the texture was mainly characterized by strong λ-fiber texture (⟨0 0 1⟩||ND) through the thickness (Fig. 2a).

After hot rolling, the strip exhibited a microstructure mainly composed of ferrite and martensite (Fig. 1b), together with medium λ-fiber, α-fiber (⟨1 1 0⟩||RD) and γ-fiber (⟨1 1 1⟩||ND) texture (Fig. 2b). Although very weak Goss texture was observed by using EBSD (Fig. 1e), it was surprised that Goss texture was absent in the ODFs. This was distinct from the well-accepted results that Goss texture originated during hot rolling and

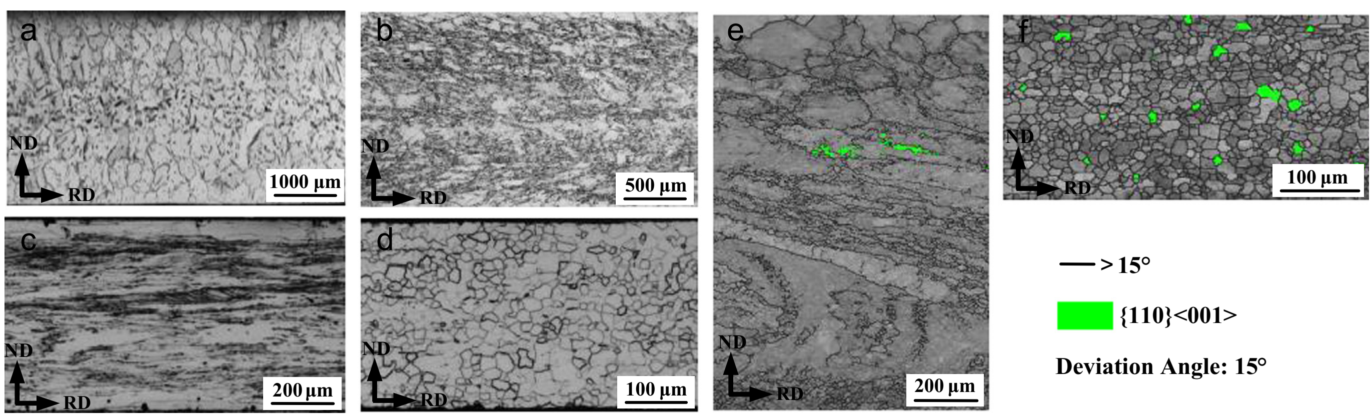

Fig. 1. Microstructure of as-cast strip (a), hot rolled strip (b), first stage cold rolled strip (c), primary annealed strip (d), EBSD pattern quality map showing Goss orientation of hot rolled strip (e) and primary annealed strip (f).

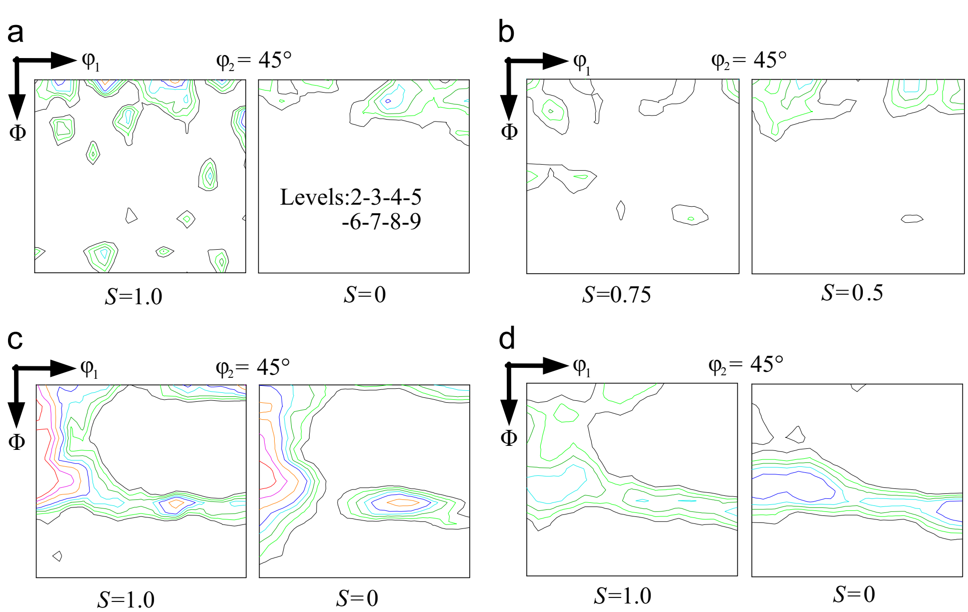

Fig. 2. Textures of as-cast strip (a), hot rolled strip (b), first stage cold rolled strip (c), and primary annealed strip (d).

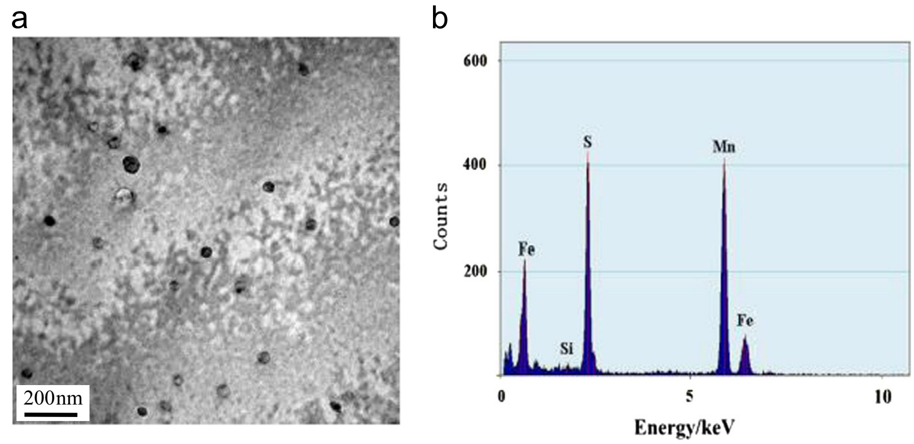

Fig. 3. TEM image showing MnS precipitates (a) and the corresponding energy spectrum (b) of the normalized strip.

dominated in the outer layers of the hot rolled band [12,19]. This may be related with lack of shear deformation due to very small hot rolling reduction applied in this work [20]. After normalizing, a microstructure composed of ferrite, martensite and carbides was produced and the texture was similar to that of hot rolled strip.

After first stage cold rolling, the strip exhibited a microstructure composed of elongated ferrite grains with in-grain shear bands and martensite (Fig. 1c). The texture was characterized by strong α-fiber and γ-fiber with the maximum at {1 1 1}⟨1 1 0⟩ component (Fig. 2c). After primary annealing, the strip showed fully recrystallized microstructure with average grain size of 13 μm with standard deviation of 3.22 (Fig. 1d), and the texture exhibited weak α-fiber and relatively strong and uniform γ-fiber (Fig. 2d). Fig. 1f shows a few Goss grains which were too weak to be detected by X-ray diffraction. It is known that these Goss grains can serve as the nuclei and large secondary Goss grains are produced by the abnormal growth of these nuclei at the expense of the primary recrystallized matrix [19]. It should be noted that the texture evolutions were different from those in conventional process. The most striking feature was that Goss texture was absent in the ODFs of primary annealed strip (Fig. 2d). This was significantly distinct from previous results in which Goss texture was the most populous component in primary recrystallization texture of two-stage route [12,13,19]. This may be related with the different textures of hot rolled strip and the cold rolling schedules.

Finely dispersed inhibitors can inhibit grain growth in primary annealing and induce secondary recrystallization by suppressing the growth of matrix grains [14]. In this work, MnS precipitates were rarely observed in the as-cast strip, which indicated that MnS precipitation may be effectively suppressed during strip casting. After normalizing, lots of finely dispersed MnS precipitates with a diameter of 20–80 nm were formed (Fig. 3). It is reported that MnS precipitates with the diameter below 100 nm are desirable to act as inhibitors [21]. The fine primary annealed grains may be attributed to the effective inhibition of grain growth by MnS precipitates (Fig. 1d).

After secondary recrystallization annealing, a macrostructure composed of very large grains with the size range of 6–40 mm was observed (Fig. 4), and the magnetic induction B_8 was as high as 1.84 T. The process in this work significantly simplified the conventional processing.

Fig. 4. Macrostructure of secondary recrystallization annealed strip.

4. Conclusions

In summary, a 0.23 mm-thick grain-oriented silicon steel sheet was successfully produced by a new process including strip casting, hot rolling, normalizing, two-stage cold rolling with an intermediate annealing, primary annealing and secondary recrystallization annealing. The secondary recrystallization annealed strip was composed of very large grains with the size range of 6–40 mm and its magnetic induction B_8 was as high as 1.84 T. It was found that the microstructure and texture evolutions were distinct from those in conventional process. The most striking feature was that Goss texture was absent in the ODFs of both the hot rolled and primary annealed strips. Besides, lots of finely dispersed MnS precipitates with the size range of 20–80 nm were formed after normalizing. These precipitates exhibited effective inhibition during primary annealing and secondary recrystallization annealing.

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