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Characterization of microstructure, texture and magnetic properties in twin-roll casting high silicon non-oriented electrical steel

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ABSTRACT

An Fe-6.5 wt.% Si-0.3 wt.% Al as-cast sheet was produced by twin-roll strip casting process, then treated with hot rolling, warm rolling and annealing. A detailed study of the microstructure and texture evolution at different processing stages was carried out by optical microscopy, X-ray diffraction and electron backscattered diffraction analysis. The initial as-cast strip showed strong columnar grains and pronounced <001>//ND texture. The hot rolled & warm rolled sheets were characterized by large amounts of shear bands distributed through the thickness together with strong <110>//RD texture and weak <111>//ND texture. After annealing, detrimental <111>//ND texture almost disappeared while beneficial {001}<210>, {001}<010>, {115}<5 −10 1> and {410} <001> recrystallization textures were formed, thus the magnetic induction of the annealed sheet was significantly improved. The recrystallization texture in the present study could be explained by preferred nucleation and grain growth mechanism.

1. Introduction

Non-oriented electrical steels usually punched in ring cores and laminated are widely used as core material for electrical machines such as motors, transformers and generators. They should meet the requirement of low iron loss and high magnetic induction in the circumferential direction [1] in order to reduce energy losses and enhance the efficiency during the process of electromagnetic transition. These magnetic properties are mainly influenced by silicon concentration, grain size, strip thickness, impurity level as well as crystallographic texture [2].

High silicon steel containing 6.5 wt.% silicon exhibits excellent soft magnetic properties such as high permeability, low eddy current and hysteresis losses at high frequencies and approximately no magnetostriction [3,4]. Therefore, 6.5 wt.% silicon steel has been suggested as the desired material [4] for iron core to promote energy conservation. However, the ductility and formability of 6.5 wt.% silicon steel are extremely limited due to ordering reactions indicated in the Fe–Si equilibrium phase diagram [5]. Thus it makes the production of the alloys into thin sheet by means of conventional rolling processes impossible. Kim [6] et al. reported that the workability of the boron-added 6.5 wt.% silicon steel can be significantly improved due to grain refinement caused by the segregation of boron to the grain boundary. Strip casting can produce thin sheets directly from the melt with a thickness close to the final product [7]. One of the advantages of strip casting is a relatively high cooling rate which can produce extremely fine solidification microstructure. Thus, it is suitable to fabricate 6.5 wt.% silicon steel by strip casting.

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It was reported by Stojakovic et al. [8] that desired <001>//ND (λ-fiber) recrystallization texture could be obtained using an as-cast Fe-3.2 wt.%Si thin sheet with strong λ-fiber texture and appropriate thermo-mechanical processing. To be interesting, strip casting can not only produce thin sheets but also generate favorable λ-fiber texture in the as-cast strip by controlling the melt superheat [9,10]. Liu [11] has successfully produced a strip-cast 3.2 wt.% silicon steel sheet with columnar grains characterized by the λ-fiber texture which can also be produced by the decarburization annealing [12,13]. After rolling and annealing, strong λ-fiber recrystallization texture was obtained and led to a high magnetic induction. Ros-Yañez et al. [14] and Liu et al. [15] respectively produced Fe-6.3 wt.%Si and Fe-6.5 wt.%Si sheets by conventional rolling process. They both found that the recrystallization texture was dominated by strong <111>//ND (γ-fiber) texture which can deteriorate magnetic induction. By contrast, strip casting may be one promising method to produce 6.5 wt.% silicon steel with favorable recrystallization texture and high magnetic induction. However, the microstructure and texture evolution of strip casting 6.5 wt.% silicon steel are still far from being understood.

In the present work, an Fe-6.5 wt.% Si-0.3 wt.% Al as-cast sheet was produced by twin-roll strip casting, and followed by hot rolling, warm rolling and annealing. This paper focuses on investigating the microstructure and texture evolution at different stages.

2. Experimental Procedure

The experimental strip with 110 mm width and 2.5 mm thickness was prepared using a vertical type twin-roll strip caster, as reported in previous literatures [8,9]. The as-cast strip was then hot rolled to 1.5 mm in thickness at 1050 °C, further warm rolled to 0.5 mm in thickness at 250 °C and finally annealed at 980 °C for 10 min in a nitrogen–hydrogen atmosphere. Textures of the as-cast, hot rolled, warm rolled and annealed sheets were quantitatively examined by measuring the three incomplete pole figures {110},{200} and {211} with $Co_{K\alpha 1}$ radiation in the Bruker D8 Discover X-ray diffraction. From the pole figures the orientation distribution functions (ODFs) were calculated by series expansion method (I_{max} = 22). The different layers are defined as the parameter $S = 2a / d$, where a represents the distance from the center layer of the sheet and d the whole thickness of the sheet. Electron backscattered diffraction (EBSD) analysis was also performed to investigate the micro-texture by OIM 4000 EBSD system equipped at FEI Quanta 600 SEM. Optical microscopy and EBSD were made on the longitudinal section defined by rolling direction (RD) and normal direction (ND). The average magnetic inductions at 800 Am^{-1}, B_8, and the iron loss at 400 Hz (1 T), W10/400, were measured using a single sheet tester in both rolling and transverse directions of the annealed specimens with 100 mm length and 30 mm width.

3. Results and Discussions

The as-cast sheet was mainly characterized by developed columnar grains, as shown in Fig. 1a. The relatively high melt superheat in the present work provided a high temperature gradient in front of the solid phase, which can promote the selective growth of columnar grains during solidification [9]. It can be found that the solidified columnar dendrites presented a deviation angle of 12–20° from ND of the strip surface. The deviation angle which was absent in the annealed columnar structure in the previous paper [12,13] may be induced by roll separating force and temperature field in the melt pool [9]. After hot rolling, the initial grains were partially recrystallized, leading to an inhomogeneous microstructure, as shown in Fig. 1b.

After warm rolling at 250 °C, a warm rolled sheet with about 110 mm width was produced, as shown in Fig. 2. No obvious cracks were observed in the middle of the sheet while some edge cracks appeared. The warm rolling microstructure was mainly composed of two types of severely deformed grains, as shown in Fig. 1c. One type of classical "smooth" grains (indicated by A and B) probably with <001>//ND orientation presented a non-characteristic microstructure. On the contrary, the other type of classical "rough" grains (indicated by C and D) probably with <111>//ND orientation was characterized by large amounts of in-grain shear bands inclined 25–35° with RD. Shear bands are linked to material instability. The formation of shear bands in materials with high stacking fault energy (such as high silicon steel) is orientation dependent [16]. It is well known that γ-grains with very high Taylor factor have a large resistance to plane strain compression (such as rolling deformation) and usually show a tendency of inhomogeneous deformation [17]. According to Nguyen-Minh [18], a smaller resistance of γ-grains to the rotated shear deformation than to the plane strain compression leads to deformation and rotation within localized bands, which results in a reduced Taylor factor of the rotated in-band orientation compared to the original {111} orientation. Hence, the occurrence of shear bands in γ-grains satisfied the geometric softening condition and was energetically more favorable. In the present study, the initial coarse columnar grains, suitable hot rolling reduction, appropriate warm rolling temperature and moderate warm rolling reduction are responsible for the prevailing of shear bands.

After annealing at 980 °C for 10 min, the warm-rolled sheet was completely recrystallized, as shown in Fig. 1d. The average grain size was about 38.3 μm. It can be found that the size of the recrystallized grains was non-uniform, which was caused by inhomogeneous warm rolling microstructure that showed different nucleation and growth behaviors during annealing.

Fig. 3 shows the texture of the as-cast strip at different thickness layers. The texture of the as-cast strip through the whole thickness was dominated by strong λ-fiber texture which was due to the selective growth of {001} columnar grains at the early stage of solidification. Interestingly, there existed a texture gradient through the thickness (Fig. 3). The texture gradient was attributed to the through-thickness microstructure heterogeneity of the as-cast strip, as shown in Fig. 1a. On one hand, the microstructure was mainly composed of fine grains due to rapid heterogeneous nucleation at the surface [9] and columnar grains in the interior. In addition, the columnar structure was characterized by different sets of columnar grains at different thickness layers. That is, only a few columnar grains could grow through the surface to the center layer. On the other hand, the orientation of columnar