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ScienceDirect
Scripta Materialia 87 (2014) 17–20
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

Evolution of cube texture in strip-cast non-oriented silicon steels

Y.B. Xu, Y.X. Zhang,* Y. Wang, C.G. Li, G.M. Cao, Z.Y. Liu and G.D. Wang

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

Received 18 April 2014; revised 19 May 2014; accepted 31 May 2014
Available online 12 June 2014

Texture evolution in Fe-1.3%Si steels with ultra-high magnetic induction produced by strip casting, cold rolling and annealing was investigated using macro-/micro-texture analysis. A new and strong {1 1 0} fiber has been founded in thin as-cast sheets. The in-grain shear bands with the Cube orientation can be observed in deformed {1 1 0}⟨1 1 0⟩ grains after cold rolling. The new Cube grains are mainly nucleated and grow within those shear bands at the beginning of recrystallization and consequently determine the overall annealing texture.

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Keywords: Twin-roll strip casting; Non-oriented silicon steels; Cube texture; Shear band; Recrystallization

High magnetic permeability and low core loss are important requirements for electrical steels. The crystallographic texture plays a most important role in effecting the magnetic properties of silicon steels. The {1 0 0}⟨0 v w⟩ texture, which has two easy magnetization directions in the {1 0 0} plane, is known to be ideal for Fe–Si magnetic materials used in rotating machines. But, it is hard to obtain strong {1 0 0} textures because they do not evolve by ordinary cold rolling and recrystallization processes in silicon steels. In recent years, some researchers obtained these textures by complicated rolling and annealing cycle, or by controlling the initial microstructure and texture of slab [1–4]. Similarly, the Cube, one of typical {1 0 0} components, is rarely observed as a dominant recrystallization texture in general. Only in a few literatures, it was reportedly formed either by cross rolling or by special annealing routes such as surface annealing and decarburization, etc. [5,6].

Park and Szpunar [7] explained the formation of Cube texture in Fe-2%Si steels by oriented nucleation theory [8]. The nucleation sites of new Cube grains, similar to the Goss grains, mainly exist within shear bands in the deformed γ-fiber grains. However, the intensity of the Goss orientation is usually much higher than that of the Cube, even though, it is well known that in non-grain-oriented (NGO) silicon steels the Goss is not the most ideal compared with the Cube. In Zhang et al.'s work [9], the Cube texture is believed to result from the initial {0 0 1}⟨0 0 1⟩ grains in a transverse-directionally aligned columnar-grained electrical steel.

The twin-roll strip casting (TRSC), during which molten steel is directly solidified into thin strips in a strip caster with the same thickness as hot-rolled ones, can realize an effective control for the initial microstructure and orientation of cold-rolled strips and hence shows a distinct advantage in producing NGO silicon steels having an ideal texture. In Liu's work [10,11], the {0 0 1}⟨5 1 0⟩ and {1 0 0} recrystallization textures were observed in 3.2%Si and 6.5%Si annealed steel sheets produced by strip casting. In author's early work [12], relatively strong Cube and Goss but weak γ fiber can be obtained in final annealed specimens of Fe-1.3%Si 2.5 mm as-cast strips. However, the mechanism on how the sharp Cube texture develops is still unclear so far.

This work focuses the microstructure and texture of a NGO silicon steel with ultra-high magnetic induction processed by strip casting, heavy cold-rolling and annealing. The aim is to clarify the origin and development mechanism of the Cube texture during different processing stages.

The non-oriented silicon steel containing 0.0036%C, 1.3%Si, 0.31%Mn, 0.22%Al was used in this study. The casting experiments were carried out by a vertical

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* Corresponding author. Tel.: +86 24 83686642; fax: +86 24 23906472; e-mail addresses: redyuanxiang@126.com; xuyunbo@mail.neu.edu.cn

http://dx.doi.org/10.1016/j.scriptamat.2014.05.019
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type laboratory twin-roll caster, and the casting rollers are made of alloy steel. The schematic diagram of the TRSC process is shown in Figure 1(a). The melt was poured into a preheated tundish, and then flowed into the molten pool composed of two casting rollers with water-cooled internally through a nozzle under the Ar shield. The melt superheat was controlled to be approximate 60 °C. The as-cast strip was cooled to room temperature by water for avoiding the $\alpha \rightarrow \gamma \rightarrow \alpha$ phase transformation during strip casting. Finally, the as-cast strips with 1.6 mm thickness and 254 mm width were obtained.

The as-cast strips were directly cold-rolled into 0.35 mm in thickness by a reversing mill. Then these specimens were respectively annealed at 650 °C for 5 s and 900 °C for 5 min in a Nitrogen–Hydrogen atmosphere for recrystallization and grain growth.

The microtexture of Fe-1.3%Si steels was performed by means of Electron Backscatter Diffraction (EBSD, HKL-Channel 5) attached to a Zeiss Ultra 55 field emission scanning electron microscope to investigate the evolution of grain orientation from strip casting to recrystallization annealing. Orientation distribution function (ODF) of the samples were measured and calculated at different thickness layer with a Bruker D8 Discover X-ray Diffractometer and Tex-Tools software. Optical microscopy and EBSD were used for microstructure and orientation analysis on RD-ND section where RD and ND are the rolling and normal directions respectively. Moreover, the magnetic induction at 5000 A m^{-1} (B_{50}) and core loss at 1.5 T by 50 Hz ($P_{15/50}$) were measured by a single sheet tester in the RD and the transverse direction (TD) of samples.

Table 1 presents the magnetic properties of 0.35 mm-thick TRSC specimen and commercial W470 steel with a similar composition after annealing. Clearly, compared with W470 steel, the core losses of TRSC materials are maintained whereas the magnetic inductions are increased by 0.11–0.13 T up to as high as 1.79–1.83 T. The superior magnetic induction is of great significance to improve the electric motor efficiency. Therefore, the TRSC route without hot-rolling and normalizing not only considerably simplifies the processing and reduces production cost, but also make a significant contribution to manufacturing the high-efficiency NGO steels.

A great number of equiaxed grains of 200–500 μm can be obtained in the as-cast strip due to high thermal conductivity of Fe-1.3%Si material and high superheat (Fig. 1b), and the texture is characterized by relatively strong {110} fiber (Fig. 1c). The microstructure of 1.6 mm thick as-cast strip is more homogeneous than that of 2.5 mm one reported by previous literatures [12], and most of the grains are separated clearly from each other by high angle grain boundaries.

Table 1. Magnetic properties of 0.35 mm-thick TRSC specimen and commercial W470 NGO steel.

Sample	$P_{15/50}$, (W/kg)		B_{50}, (T)	
	RD	TD	RD	TD
TRSC	4.1	4.3	1.83	1.79
W470	4.0	4.3	1.70	1.68

The majority of {110} fiber components usually occurred in hot rolled strips are Goss orientation, and there is occasionally a low volume fraction of $\{110\}\langle110\rangle$ (also called rotated Goss) grains. The Goss is generally believed to be associated with local shear deformation during hot rolling [13]. However, the origin of $\{110\}\langle110\rangle$ orientation is quite complicated, and so far there is no clear explanation. In the present as-cast strip, there are pronounced {110} fiber components such as strong $\{110\}\langle110\rangle$ and $\{110\}\langle221\rangle$, and a slightly weak $\{110\}\langle223\rangle$ texture whose intensities are much higher than those of {100} fiber components. Of course, it is undeniable that there are also some deformation textures such as $\{111\}\langle110\rangle$ orientation due to solidification structure being hot rolled at a certain reduction. Here, even for those textures close to Goss orientation, its formation mechanism could not be explained by local shear deformation usually applied in hot rolling. It is possibly attributed to deformation behavior of solidification structure formed at high temperatures, particularly for the origin of $\{110\}\langle110\rangle$ grains. During strip casting, the liquid steel flows into the water-cooled internally casting rolls and freezes against the surface of rolls. The smaller exit thickness of strip, the higher superheat of molten steel and the lower thermal conductivity of material of the rolls could lead to the forming solid shell being thicker than half roll gap width at the exit of the roll gap. Meanwhile, the excess part of solid shell (i.e., the shell part thicker than half roll gap width) at the exit of roll gap is to be rolled with a certain amount of deformation at extremely high temperature (greater than the exiting temperature from rolls, i.e., ~1300 °C), which is most likely to be responsible for the formation of $\{110\}\langle a-aw\rangle$ textures.

At 67% and 77% cold-rolling reductions (corresponding to 0.5 and 0.35 mm in thickness of cold-rolled sheets respectively), remarkably inhomogeneous deformed microstructures which are mainly composed of two different types of elongated grains can be obtained as shown in Figure 2(a) and (b). Grain A and C, are elongated grains with a low dislocation density, which usually corresponds to the $\{100\}$–$\{114\}$ $\langle011\rangle$ orientations having low stored energy, as shown in Figure 2(c). Grain B and D show a lot of in-grain shear bands. These

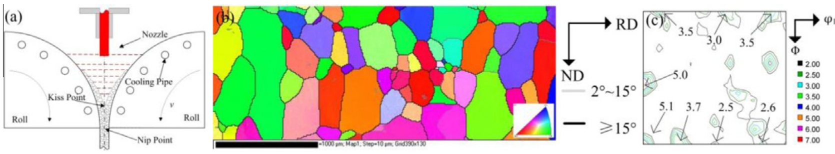

Figure 1. Schematic diagram of the TRSC process (a), EBSD orientation map (b) and ODF of XRD data displayed at $\varphi_2 = 45°$ section (c) of the as-cast strip.

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