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# Through process texture evolution of new thin-gauge non-oriented electrical steels with high permeability

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ABSTRACT

This paper demonstrated new methods for producing high permeability thin-gauge non-oriented electrical steels with columnar-grained 3.05% Si cast slabs containing carbon and MnS precipitates, and the texture evolution was investigated. The magnetic properties of 0.2 mm final sheets were greatly improved by the optimized texture comprising {100}⟨0vw⟩ and strong {hk0}⟨001⟩ components, and the best combination of $B_{50}$ and $P_{1.5}$ was exhibited as 1.764 T and 2.45 W/kg respectively. The texture evolution depended on both the moderate inhibiting effect of coarse MnS precipitates and rolling methods. {100}⟨0vw⟩ texture could be retained from columnar grains, and strong {hk0}⟨001⟩ texture was obtained by two-stage rolling in distinct ways: On one hand, for the sample corresponding to low second-stage rolling reduction of 60%, based on the large grain size prior to cold rolling, the higher strain of first-stage cold rolling promoted {hk0}⟨001⟩ nucleation during intermediate annealing. {hk0}⟨001⟩ grains were further increased after moderate second-stage cold rolling and decarburization annealing, consequently leading to the final strong {100}–{110}⟨001⟩ texture and uniform microstructure by quantity and size priorities, and the optimum magnetic properties were achieved; on the other hand, secondary recrystallization occurred on fine-grained decarburized matrix at higher second-stage rolling strains and greatly improved the magnetic induction in RD. The level of abnormal Goss grains growth was decreased in the sample corresponding to 80% second-stage rolling reduction, and normal growth of other beneficial grains lowered the magnetic anisotropy, suggesting another potential way for non-oriented electrical steel production. In addition, the effect of carbon was discussed.

## 1. Introduction

Non-oriented (NO) electrical steels are usually used as motor core materials. Recently, with increasing application of motors at varied frequencies, thin-gauge NO electrical steel has been more focused for its low iron loss, especially at high frequencies [1,2]. However, rather low magnetic inductions in the existed thin-gauge NO electrical steel products would cause high copper loss. Therefore, based on texture optimization, to improve the magnetic inductions of thin-gauge NO electrical steel is essential for high-efficiency motors.

Texture optimization in NO electrical steels includes strengthening beneficial {100}⟨0vw⟩ and {hk0}⟨001⟩ textures as well as weakening harmful {111}⟨uvw⟩ texture, and it could be realized by modifying processing routes. Larger grain size prior to cold rolling reduces {111}⟨uvw⟩ nucleation sites at grain boundaries and promotes {hk0}⟨001⟩ nucleation at shear bands, and moderate rolling reduction favors the retention of Goss texture originating from hot rolling [3–7]. At the meanwhile, retaining {100}⟨0vw⟩ texture of columnar grains provides a potential way for producing NO electrical steel [8,9].

In contrast, the magnetic properties of grain-oriented (GO) electrical steel are improved by a different mechanism, namely obtaining sharp Goss texture by abnormal Goss grain growth, and homogeneously dispersed small inhibitor particles, fine-grained primary recrystallization microstructure and several Goss nuclei are the prerequisites for the occurrence of secondary recrystallization [10]. Sharp Goss texture benefits the magnetic properties along rolling direction, while lead to strong magnetic anisotropy, implying that the level of Goss grains growth needs to be controlled when being applied for NO electrical steel production.

This paper explored new methods for producing thin-gauge non-oriented electrical steel with columnar-grained 3.05% Si cast slab having carbon and inhibitors, and high permeability was pursued by compromising {100}⟨0vw⟩ and strong {hk0}⟨001⟩ texture. Given that the fraction of hysteresis loss in overall iron loss

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greatly increases in thin-gauge electrical steels, the optimized crystallographic texture could reduce iron loss as well. The texture evolutions along the processing routes were studied to provide theoretical basis for magnetic properties optimization, meanwhile, normal or abnormal growth of Goss grains was discussed combined with inhibitors analysis.

## 2. Experimental

The initial materials were two columnar-grained cast slabs with the same thickness of 30 mm: S1 containing 0.045%C, 0.1% Mn, 0.015%S and 3.05%Si and S2 containing 0.002%C, 3%Si as well as ultra-low contents of Mn and S. Both S1 and S2 were heated at 1320 °C for 30 min and hot rolled to 2 mm, then normalization annealing at 1120 °C for 5 min in nitrogen atmosphere was carried out, followed by quenching in boiling water. As illustrated in Table 1, the annealed hot bands were cold rolled to 0.2 mm by different cold rolling methods, and all the samples by two-stage rolling were annealed at 850 °C for 5 min between two rolling stages. Afterwards, the cold rolled samples containing 0.045%C were decarburized at 850 °C for 8 min in mixed atmosphere, followed by final annealing at 950 °C for 20 min with a high heating rate of 300 °C/min in hydrogen. Initial materials S1 and S2 were compared to clarify the effects of carbon and MnS precipitates. To exclude the effect of other processing parameters, the S2 rolled sample was also subjected to primary recrystallization annealing at 850 °C for 8 min and subsequent final annealing, which is same as those applied to S1 samples.

Textures in surface and center layers of annealed hot bands S1 were measured with a Bruker D8 Advance X-ray diffractometer, and the microstructure was investigated with optical microscopy. Textures and microstructures of other investigated samples were measured with EBSD technique. The EBSD system was attached to a Zeiss Ultra 55 field emission scanning electron microscope (FESEM), and all the measurements were performed on the cross sections defined by the rolling and normal directions (RD and ND). The size distribution of MnS precipitates was determined with the same FESEM. Magnetic inductions at 5000 A/m ($B_{50}$) and iron losses at 1.5 T by 50 Hz ($P_{1.5}$) were measured by a single sheet tester along RD and the transverse direction (TD) of samples sheared to 50*50 mm.

## 3. Results and discussion

The magnetic properties of all the final sheets are presented in Fig. 1. Compared with the B20AT1500 steel products exhibiting $B_{50}$ = 1.64 T and $P_{1.5}$ = 2.48 W/kg (indicated at the lines in Fig. 1), all the samples in this study show improved magnetic inductions, among which the increases of $B_{50}$ values of samples 1–4 are much larger, implying the effect of carbon and MnS particles. In particular, superior magnetic inductions are achieved in the samples prepared by two-stage cold rolling methods, although in different ways: On one hand, the best magnetic properties with mean values of $B_{50}$ and $P_{1.5}$ as 1.764 T and 2.45 W/kg respectively are obtained in sample 2, and low differences between $B_{50}$ and $P_{1.5}$ values along different directions are ideal for NO electrical steel; On the other hand, the highest value of $B_{50}$ along RD is shown to be 1.856 T in sample 3, while $B_{50}$ value lower than 1.63 T along TD could not meet the requirement of NO electrical steel. In addition, it is worth to note that sample 4 reveals higher $B_{50}$ value along RD than sample 2, accompanied with lower magnetic anisotropy than sample 3, thus suggesting another potential method for NO electrical steel production.

Magnetic properties of the final samples depend on the microstructure and texture development along processing routes. In the following sections, the microstructure and texture evolution of samples 1–4 with higher permeability will be firstly investigated, with focus on the effects of thermomechanical parameters. Coarse microstructure in the annealed hot bands in Fig. 2(a) is one of the key factors reducing γ-fiber texture after cold rolling and annealing, meanwhile, no elongated α-fiber grains, which are harmful for microstructure homogenization and texture optimization, are observed in the central layer [4]. Beneficial {100}⟨0vw⟩ texture was greatly retained from initial columnar grains, as described in our previous studies [8,9], and it has been confirmed that {100}⟨0vw⟩ texture in initial materials and hot bands is essential for the strong {100}⟨0vw⟩ texture along the processing routes [11,12]. Meanwhile, the retention of Goss texture could be expected as well, especially when the rolling strain is moderate. As shown in Fig. 2(d), compared with industrial GO electrical steel, MnS precipitates in this study display larger size ranging from 80 to 150 nm, which is assumed to be related with the coarsening during normalization annealing. Both the large-sized MnS particles and less thickness of final samples contribute to decreasing inhibiting effect along the processing routes, suggesting different growth behavior of Goss grains from industrial GO electrical steel. In addition, considering that the precipitation and size of MnS particles are mainly determined by hot rolling and normalization annealing, the distribution of MnS should be similar in all the samples prepared with S1, which will be verified later. This implies that the texture evolution difference in samples 1–4, especially before the onset of secondary recrystallization, is mainly determined by rolling methods.

After cold rolling and decarburization annealing, the recrystallization microstructure of one-stage processed sample is inhomogeneous, as shown in Fig. 3(a). Besides the decreasing inhibition of coarse MnS particles, the large size of {100}⟨021⟩–{113}⟨361⟩ oriented grains is attributed to the less nucleation sites inside {001}–{112}⟨110⟩ deformed regions, and strong {h,1,1}⟨1/h,1,2⟩ texture is widely reported in BCC metals after heavy deformation and recrystallization [13,14]. {h,1,1}⟨1/h,1,2⟩ grains grow preferentially due to size advantage during the final annealing, which could not improve the magnetic inductions greatly.

Two-stage cold rolling methods promote the homogenization of decarburized microstructure in Fig. 4, which is also affected by the ratio of first-stage rolling reduction to the second-stage one. For the decarburized samples corresponding to second-stage rolling reduction of 60%, Fig. 4(a) presents coarser recrystallization microstructure, and the stronger {hk0}⟨001⟩ texture as well as weaker γ-fiber texture is depicted. The coarse microstructure after

**Table 1**
Processing parameters of cold rolling.

| Initial materials | Processing routes | Cold rolling methods | Final samples |
|---|---|---|---|
| S1 | Route 1 | One-stage rolling | Sample 1 |
| S1 | Route 2 | Two-stage rolling, with the second stage reduction of 60% | Sample 2 |
| S1 | Route 3 | Two-stage rolling, with the second stage reduction of 70% | Sample 3 |
| S1 | Route 4 | Two-stage rolling, with the second stage reduction of 80% | Sample 4 |
| S2 | Route 2 | Two-stage rolling, with the second stage reduction of 60% | Sample 5 |