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The quenching effects of hot band annealing on grain-oriented electrical steel

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A B S T R A C T

The grain-oriented electrical steels are widely used in transformers, which demand low iron loss and high induction of core materials. In order to obtain good magnetic properties, a series of rolling, annealing and coating processes are carried out. Hot band annealing, which influences the ductility for cold rolling and the development of AlN inhibitors, is one of the most important processes. This study investigated the phases and different kinds of precipitations in microstructures of annealed hot band by means of the optical and electronic microscopies. On the other hand, a Themo-Calc software and the solubility product equations of AlN are used to calculate the phase diagram of Fe–Si–C alloy and the amount of AlN at high temperature. Microstructures including ferrite, cementite, pearlite and martensite were observed. The size and shape of precipitates, i.e. GP Zone, TiN, AlN, MnS, oxide and carbide, were identified. The relationship between the amount of nano-scale AlN and magnetic properties indicated that the suitable cooling method resulted in lower iron loss and higher magnetic induction. The result could help to realize the following microstructure evolution and mechanism of inhibitors in grain-oriented electrical steel.

1. Introduction

Electrical steels can be divided into two categories, i.e. non-oriented electrical steels (NOES) and grain-oriented electrical steels (GOES) [1]. NOES, which contain 0–3.5% of silicon and have the orientation relationship (OR) of crystallographic {1 0 0} ⟨0*uv*⟩ parallel plane of the sheet and the rolling direction of the electrical steels, are used for numerous core-laminated products such as turbines and motors mainly. On the other hand, GOES, which contain 3.0–3.8% of silicon and have the preferred crystallographic {1 1 0} ⟨0 0 1⟩ OR (Goss OR), are usually used in stationary electrical machinery, e.g. transformers [2,3]. GOES exhibit superior magnetic properties along the rolling direction resulting from their anisotropic Goss OR. In order to obtain the ideal Goss texture, e.g. most are within 7° to the rolling direction, the inhibitors such as MnS, AlN, etc., which have the size of nanometer scale, play an important role in controlling the grain growth of the first and the secondary recrystallizations [4]. The varied inhibitors also control the evolution of the microstructure when the specimens experienced different thermal cycles of annealing. The most important influence of the precipitations is that they affect the final magnetic properties of the products directly [4].

There are several basic processes to produce the electrical steel. The procedures include steel making, hot rolling, normalizing annealing (hot band annealing), cold rolling, first recrystallization annealing, secondary recrystallization annealing and heat flattening coating [5,6]. The normalizing annealing contributes to the good ductility on cold rolling, to promote the secondary recrystallization and better magnetic properties of product. In addition, the quenching stage of normalizing annealing supplies the stable and fine dispersion of precipitations, which act as inhibitors on recrystallization. Hence, the appropriate hot band annealing would be acquired to achieve the optimum inhibitive ability to control the grain growth [7]. On the other hand, the normalizing annealing also controls the phase transformation of $\gamma \rightarrow \alpha$, i.e. changes the microstructure and influences the evolution of the microstructure in the further procedures.

Few studies [8,9] have been published on the analysis of the microstructures and texture evolution. Moreover, the observation of precipitations, the so called inhibitors, has been widely discussed [10–13]. Although many researchers have investigated the dominant phases such as AlN, MnS on the annealed hot band, little attention has been paid to describe the detailed microstructures on normalizing annealing. Therefore, the aim of this study is to investigate and categorize the possible phases that include microstructures and precipitations on the stage of the normalizing annealing. Furthermore, the present paper also reports the relationship between nano-scale AlN and the magnetic properties in detail. The analysis presented in this paper may help to clarify the phase transformation and the size

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and distribution of the precipitations. The results may also provide a useful reference for the further evolution of the texture and microstructures.

2. Material and methods

The materials were 3% silicon–iron electrical steels. After continuous casting, the slabs of silicon steels were reheated at high temperature and subsequently hot rolled into thickness of 2.3 mm. The hot band passed through a continuous annealing furnace and was treated by a normalizing annealing, as shown in Fig. 1. The specimens were heated to high temperature to dissolve the precipitations and to form γ phase. Then the hot bands were initially cooled at a rate of 2 °C/s, and subsequently cooled down to room temperature with five different cooling conditions (denominated as H1–H5). Phase transformation of $\gamma \rightarrow \alpha$ occurred during the cooling processes. As a result of the different cooling methods, various size and amount of precipitations were obtained. Accordingly, the quenching effects on the final magnetic properties could be studied.

After hot band annealing, the micrographs and energy dispersive spectrum of the samples were analyzed by JOEL JSM-6340F SEM. In order to achieve high-resolution observation, JOEL JEM-100CX II TEM, Philips CM20 STEM and Philips TECNAI F20 FEG-TEM were used for analysis of precipitation and microstructure.

3. Results and discussion

3.1. Microstructures

Typical photomicrographs after normalizing annealing are shown in Fig. 2. The microstructure of subsurface layer is likely the most important zone to influence the following processes (refer to Refs. [8,9]). Consequently, the following discussion was focused at this region.

Fig. 3 shows that H3–H5 cooling conditions, which cooled slowly through phase transformation temperature (see Fig. 1), resulted in uniform grains. As shown in Fig. 4, there is a two phase region where ferrite and austenite coexist at around 800–1300 °C in high silicon steels (Si > 2 wt%). When the specimens were annealed at high temperature, some α phases transformed to austenite (γ). The γ phase, then, transformed to ferrite (α) again in the period of cooling. As the steel cooled and passed through the phase transformation temperature, the new ferrite became supersaturated with higher contents of N and C. Thus, the cooling rate passing the phase transformation temperature would have great influence on the grain size of the ferrite grain and the type of hard phase. While the cooling rate was low such as H3–H5 (see Fig. 1),

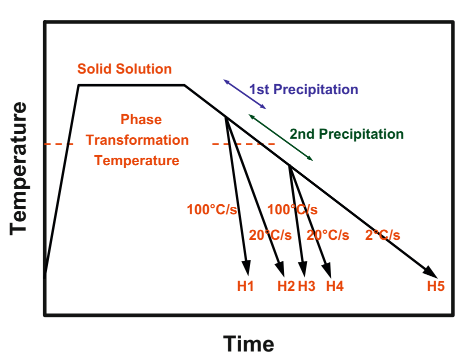

Fig. 1. Schematic diagram of hot band annealing cycle.

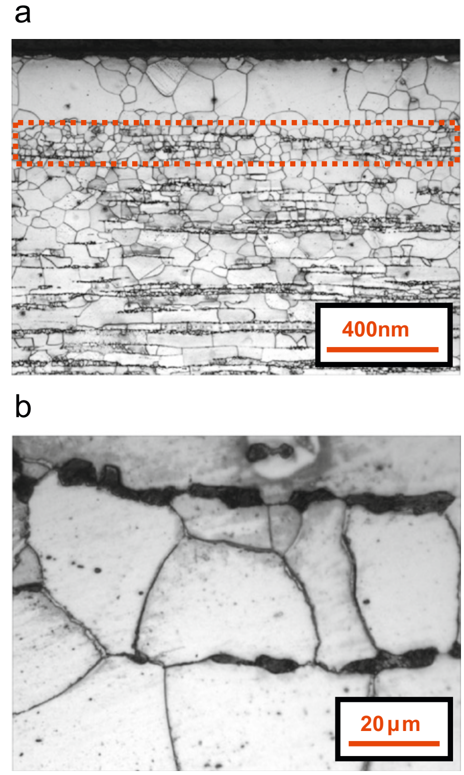

Fig. 2. Photomicrographs obtained from the annealed hot band: (a) half of thickness of the specimen and (b) subsurface layer.

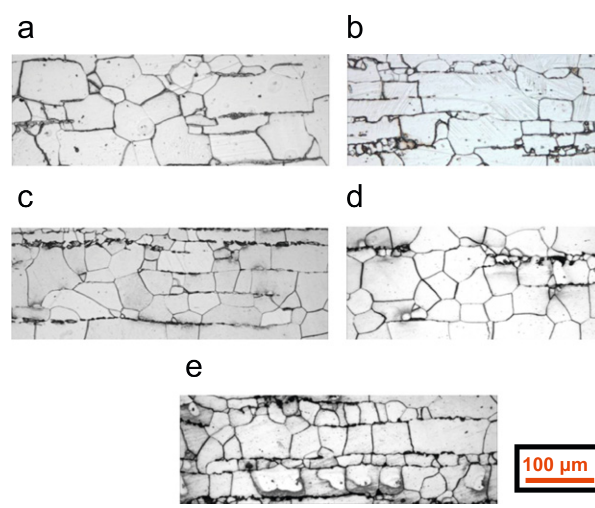

Fig. 3. Photomicrographs located at subsurface layer obtained from the annealed hot band: (a)–(e) were observed from H1–H5 quenching conditions.

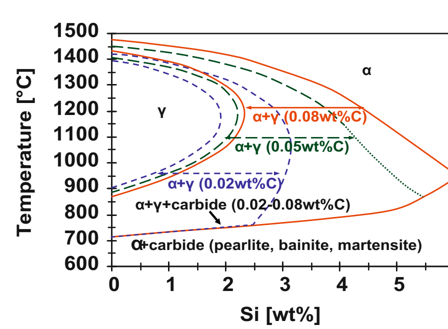

Fig. 4. Fe–Si–C phase diagram (calculated with Thermo-Calc software by courtesy of National Sun Yat-sen University) [20].