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Effect of annealing atmospheres on secondary recrystallization in thin-gauge grain-oriented silicon steel: Microstructures and textures

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ABSTRACT

By controlling the onset temperature of secondary recrystallization and the temperature interval for grain growth, the annealing atmosphere is the key factor affecting the grain size and texture of grain-oriented silicon steel. The thin-gauge cold-rolled grain-oriented silicon steel (TG-CRGO) is not only more sensitive to annealing atmosphere than the thick-gauge grain-oriented silicon steel, but also requires a different annealing atmosphere. In this paper, the evolution of microstructures and textures in 0.18 mm TG-CRGO steel during high-temperature annealing in five different annealing atmospheres are detected through EBSD technique. The results show that excellent magnetic properties ($\boldsymbol{B}_8$=1.93 T) can be obtained when annealing atmosphere as 75%N_2+25%H_2 (volume ratio). Secondary recrystallization occurs in all the specimens that were prepared in five different annealing atmospheres, which causes significant differences in secondary recrystallized microstructures and textures. As N_2 content rises, the average secondary recrystallized grain sizes increased and reaches a maximum average grain size in 75%N_2 atmosphere and then decreases along with N_2 content over 75%. When N_2 content is 75%, Goss grains show preferential abnormal growth at 1050–1055 °C, which is a very narrow temperature range for secondary recrystallization. In conclusion, proper annealing atmosphere is one of the important measures to control and enable the grain-oriented silicon steel to get the sharp Goss texture.

1. Introduction

The gain-oriented silicon steel is mainly applied as an iron core of a transformer and is called as the “handicraft” in the steel industry. The steel requires a long process and a complicated technique for production. Sharp Goss [{110} < 001 >] texture can be obtained by controlling rolling and annealing parameters accurately, and the less deviation of the orientation of the secondary grain from exact Goss leads to higher magnetic induction. Aside from high magnetic induction induced by sharp Goss texture, low iron loss is also required to meet the requirements for energy saving, emission reduction, and size reduction of transformer. Reducing the thickness of final products can also decrease the iron loss of silicon steels. The thickness of grain-oriented silicon steel develops in the following order: 0.35 mm → 0.30 mm → 0.27 mm → 0.23 mm. To date, steel as thin as 0.18 mm, and even thinner, have been developed. The low temperature hot rolled plate is necessary to reduce the energy consumption and cut surface oxidation loss of hot rolled plates in the modern industry. However, this technique poses a significant challenge in industrial production. For example, nitriding should be incorporated into the subsequent processes. Even so, TG-CRGO steel preparation process is still the develop trend to produce high-performance grain-oriented silicon steel.

Based on the 2.23–2.5 mm industrial hot-rolled slab, when the thickness of is reduced to 0.20 mm, high cold rolling reduction (higher than 90%) makes it difficult to obtain Goss texture by secondary recrystallization [1]. The secondary recrystallized microstructure and texture rely on the primary recrystallized microstructure and texture after decarburizing annealing process. The Goss primary recrystallized grains have two origins. One is the initial Goss-oriented grains in the hot-rolled plate [2], and the other is the nucleation inside shear bands in {111} < 112 > deformed grains during cold rolling [3,4]. For 0.18 mm cold rolled plate created through one-step cold rolling, the rolling reduction is 92%, which is very detrimental for the retention of Goss grains. The proportion of Goss grains in the annealed microstructure would be very low, far less than those of deviated Goss and Brass ({110} < 112 >) grains. Therefore, in terms of “nuclei” number for

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secondary recrystallization, Goss grains do not show any advantage over the deviated Goss and Brass grains. The study revealed that deviated-Goss and Brass grains are mainly formed in an α-fiber oriented deformed microstructure during annealing, and no direct relation exists with the deviated-Goss and Brass grains in the original hot-rolled plate [5]. Moreover, these grains are usually larger than Goss grains. Our previous work [6] showed that the cold-rolled texture of TG-CRGO steel is mainly characterized as strong α-fiber and weak γ-fiber, and these are beneficial for the nucleation of deviated-Goss and Brass grains during primary recrystallization annealing. Therefore, the main task is to inhibit abnormal growth of deviated-Goss and Brass grains in the annealing process of TG-CRGO steel.

In TG-CRGO steel, two main factors adversely affect the formation of Goss texture during secondary recrystallization. First, the decrease of Goss primary grains in the decarburizing annealing microstructure [7]; second, the thin-gauge sheet is more sensitive to the atmosphere during high-temperature annealing, and the inhibitors are more easily aged in the heating process, leading to the coarsing of surface microstructure [8]. Therefore, controlling the decomposition rates of inhibitors in the high-temperature annealing and obtaining perfect Goss texture is crucial for producing TG-CRGO steel. The atmosphere in high-temperature annealing is highly correlated with the component system, plate thickness, and acquisition method and inhibitor distribution status. The grain-oriented silicon steel with different component systems requires a totally different high-temperature annealing atmosphere. For the conventional high-temperature Hi-B steel with MnS and AlN inhibitors, the optimal N_2:H_2 ratio of final annealing atmosphere is 1:3 [9]. Takamiya [10] reported that when using inhibitors of MnSe and AlN, which can be formed by the addition of a small amount of Se and Sb into the conventional high-temperature Hi-B steel, the content of H_2 in the annealing atmosphere could be further increased. The medium-temperature copper-bearing steel mainly takes Cu_2S as the inhibitor. Given that the hydrogen is inclined to lower sulfur content quickly, that is, the number of Cu_2S particles is reduced, in the heating process, the H_2 content should be limited to 10% in the annealing atmosphere [11]. Regarding the production of TG-CRGO steel with low temperature slab reheating technique, the original component system, the acquisition method of inhibitors and the thickness of final sheets are significantly different from those of the steels mentioned above. Reports on the effect of annealing atmosphere on TG-CRGO steel are limited, and the mechanism by which different annealing atmospheres affect the secondary recrystallization remains unknown.

In this paper, 0.18 mm TG-CRGO steel is prepared through industrial hot-rolled plates. The secondary recrystallization microstructures and textures in five different annealing atmospheres are then compared, and the effect of high-temperature annealing atmospheres on the secondary recrystallization behavior in the production of TG-CRGO steel is discussed. The mechanism of selective abnormal grain growth in TG-CRGO steel during secondary recrystallization is analyzed as well.

2. Experimental procedure

The industrial hot-rolled slab is utilized as the initial material in this study. The chemical compositions are as follows (mass fraction, wt %): 0.05%C, 3.0%Si, 0.10%Mn, 0.005%S, 0.027%Al, 0.006%N, and 0.03%Sn. After normalizing annealing, the hot-rolled slab is cold rolled to 0.18 mm through one-step cold rolling. Then, the rolled sheets are subjected to decarburizing annealing at 870 °C for 4 min under wet atmosphere and nitriding at 750 °C for 90 s in atmosphere of nitrogen, hydrogen and ammonia (N_2:H_2:NH_3=2:6:1, L/min). Afterwards, the specimens are coated with MgO and annealed in five different atmospheres. The specific process parameters are illustrated in Fig. 1. At 950–1075 °C, interrupted specimens are collected to investigate the changes of their microstructures and textures in different annealing

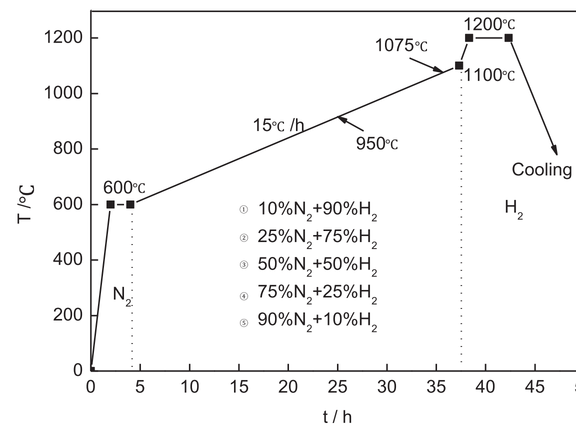

Fig. 1. Annealing experimental schematic diagram.

atmospheres. The nitrogen content in different interrupted specimens was measured by chemical composition analysis. The microstructures and textures are measured with electron backscattered diffractometer (EBSD) attached to Zeiss Ultra 55 field emission scanning electron microscope (FESEM). The magnetic properties of finished specimens are measured through NIM-2000E magnetic measuring instrument along RD at 800 A/m (B_8) by 50 Hz.

3. Results and discussions

3.1. Magnetic properties

Fig. 2 shows the relationship between different annealing atmospheres and the final magnetic induction of 0.18 mm TG-CRGO steel specimens. As shown, for 0.18 mm specimen, the optimal ratio of high-temperature annealing atmosphere for the magnetic induction value B_8 is 75%N_2+25%H_2 and B_8 reaches 1.93 T.

3.2. Evolution of secondary recrystallization microstructures and textures

Fig. 3 shows the secondary recrystallized grains and textures of the specimens after high-temperature annealing, and all the specimens in five different annealing atmospheres underwent secondary recrystallization completely. According to {200} pole figures (Fig. 3(f-j)) for each specimen, the orientations of most grains show approximately 7° deviation from exact the Goss orientation (called deviated Goss grains in this paper), whereas the proportion of Brass grains is very small. Therefore, the decreased magnetic property can be deduced to be mainly caused by the abnormal growth of deviated Goss grains other

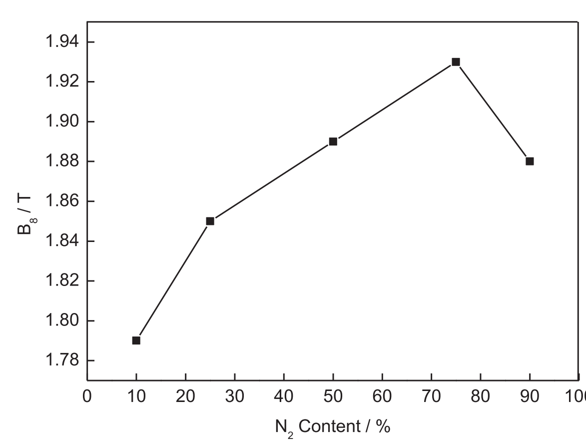

Fig. 2. Relationship between high-temperature annealing atmospheres and magnetic induction value B_8.