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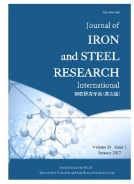

Microstructure, texture and precipitates of grain-oriented silicon steel produced by thin slab casting and rolling process

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ABSTRACT

A grain-oriented silicon steel strip with AlN as main inhibitor was produced by thin slab casting and rolling (TSCR) process. The microstructure, texture and precipitates of the hot-rolled strip were investigated by use of optical microscope (OM), X-ray diffractometer, transmission electron microscope (TEM) and energy dispersive spectroscope (EDS). The result shows that the microstructure and texture exhibit a through-thickness gradient similar to that of the hot-rolled strip produced by conventional high-temperature slab-reheating process; the preferred orientation varies from $\{110\}\langle 001\rangle$ in the surface layer to $\{001\}\langle 110\rangle$ in the center layer, and the Goss texture with a maximum intensity mainly concentrates on the surface layer. In addition, some other texture components, for example rotated Goss texture, form in the 1/4 thickness layer, which are not observed in the hot-rolled strip produced by conventional high-temperature slab-reheating process. The precipitates in the hot-rolled strip are mainly (Mn,Cu)S and AlN compound particles with dimension of 100－200 nm, and the fine precipitates are significantly less than that in the hot-rolled strip produced by conventional high-temperature slab-reheating process. Moreover, the areal density of the fine precipitates in the center layer is more than that in the surface layer.

1. Introduction

Grain-oriented silicon steel containing about 3 wt.% Si is widely used as the core material of transformers and generators for its high permeability and low core loss along the rolling direction[1,2], and its magnetic properties are closely related to the sharpness of Goss texture ($\{110\}\langle 001\rangle$) which is evolved by secondary recrystallization. It is well known that the finely-dispersed secondary phase particles such as MnS and AlN in Fe-3 wt.% Si steel, which called inhibitors, play an important role in controlling the development of Goss texture during secondary recrystallization. In order to improve the sharpness of Goss orientation, a complicated manufacturing method, including continuous casting, reheating, rough rolling, finish rolling, normalization, cold rolling and annealing, is adopted in conventional high-temperature slab-reheating process, during which slabs are always reheated over the solution temperature of the inhibitor substances (above 1 350 ℃) and held for sufficient time to make the inhibitor substances completely solute and then finely precipitate during hot rolling or cooling process[3,4]. However, the application of conventional high-temperature slab-reheating process results in high energy consumption and high manufacturing cost. Hence, substantial efforts have been made to reduce slab-reheating temperature, and several low-temperature slab-reheating methods have been developed all over the world[5-9]. In principle, it is known that thin slab casting and rolling (TSCR) process is especially suitable for producing grain-oriented silicon steel due to combining low-temperature slab-reheating technique with compact process.

However, there are a lot of differences between TSCR process and conventional process in slab casting, reheating schedule, rolling process, delivery

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speed on the runout table and so on. It was reported that for low-carbon steels, some important differences exist in microstructure, precipitates and mechanical properties between the TSCR products and conventional ones[10-12]. As is known to all, it is crucial to obtain the suitable primary Goss grains as the nuclei for secondary recrystallization and prepare for favorable surroundings for growth during hot rolling stage[13]. Therefore, how these differences between TSCR process and conventional high-temperature slab-reheating process influence the microstructure, texture and precipitates of the hot-rolled strip is of great concern. In this work, a grain-oriented silicon steel strip with AlN as main inhibitor was produced by TSCR process. The microstructure, texture and precipitates of the hot-rolled strip were characterized and investigated. The differences in texture and precipitations between TSCR process and conventional high-temperature slab-reheating process were also discussed.

2. Experimental

2. 1. *Material*

A grain-oriented silicon steel strip with AlN as main inhibitor was produced by TSCR process. The chemical composition (in wt. %) of the specimens used is C 0. 05, Si 3. 47, P 0. 009, Al 0. 027, N 0. 006, S 0. 009, Cu 0. 035, Mn 0. 096, and Sn 0. 048. The process was as follows: smelting in a 170 t converter→ladle furnace (LF) refining→compact strip production (CSP) casting→reheating→hot rolling→cooling→coiling. The liquid steel after steelmaking was teemed into the tundish of the continuous casting machine, and was cast into slab with thickness of 55 mm via liquid core reduction. Then, the slab was transported to the tunnel furnace at about 900 ℃ and soaked at 1150 ℃ for 30 min before hot rolling. Subsequently, the slab was hot rolled to 2. 5 mm in thickness by 7 rolling passes, and finishing rolling temperature and coiling temperature were 880 ℃ and 650 ℃, respectively.

2. 2. *Characterization of microstructure, texture and precipitates*

Metallographic specimens of the hot-rolled strip were machined, polished and etched with 4 vol. % nital. The microstructures along the longitudinal section (RD-ND) and cross section (TD-ND) were observed with an optical microscope (RD: rolling direction; ND: normal direction; TD: transverse direction). The average ferrite grain size of the hot-rolled strip was measured using the line intercept method. The texture intensities were measured by a RIGAKU D/MAX-2500 X-ray diffractometer across the sample thickness. To this purpose, normalization thickness layers $S=0$, 0. 5, 1. 0 were regarded. Here, the thickness layer is defined as the parameter $S=2a/d$, where a represents the distance away from the center layer and d is the thickness of the hot-rolled strip. The orientation distribution functions (ODFs) were calculated from three incomplete pole figures {200}, {110} and {112} by the series expansion method ($I_{max}=22$). In order to characterize the precipitates of the hot-rolled strip, carbon extraction replicas of different thickness layers were prepared, and the morphological observation as well as the chemical analysis of the precipitates were performed by using a JEM-2100F transmission electron microscope (TEM) equipped with an energy dispersive spectrometer (EDS).

3. Results and Discussion

3. 1. *Microstructure and texture of hot-rolled strip*

According to the thermodynamic calculations for the investigated grade of steel, it consists of ferrite and a small amount of austenite at high temperature, and this indicates that the hot rolling occurs in two-phase region which is dominated by ferrite phase. The optical micrographs of the hot-rolled strip in the RD-ND plane and the TD-ND plane are shown in Fig. 1. It can be seen that the microstructure consists of ferrite and a small amount of pearlite, and the ferrite grains are inhomogeneous through the thickness. At both surface regions, the microstructure is characterized by fine equiaxed grains with an average grain size of 50 μm, whereas the coarse and ribbon-like grains which are elongated along the rolling direction exist in the center regions. It is known that the stacking-fault energy (SFE) of the ferrite is very high, which is difficult to get almost recrystallized structure after hot rolling. The grains in the surface regions are subjected to strong shear deformation, which leads to a high dislocation density and a high stored energy, and thus recrystallization occurs, resulting in very fine equiaxed grains in the surface regions. On the other hand, the grains in the center regions are dominated by plane compression deformation and experience much less shear deformation, which cannot lead to enough stored energy for recrystallization. As a result, the grains in the center regions typically show an elongated pancake-type morphology[14,15].

Due to the through-thickness microstructure inhomogeneity, a through-thickness texture gradient was also observed. ODFs at $\varphi_2=0°$ and $\varphi_2=45°$ sections of the hot-rolled strip are given in Fig. 2. According to the ODF sections shown in Fig. 2, it is found that the texture along the thickness direction in the hot-rolled strip changes obviously. The Goss texture, {110}<001> component, distributes preferentially in the surface layer ($S=1$), together with