Evolution of Texture in High Permeability Grain Oriented Silicon Steel Produced by Casting Thin Slab and Rolling Process

Fan Li-feng¹,², Qiu Sheng-tao¹,², Xiang Li¹,² and Tang Guang-bo³

¹State Key Laboratory of Advanced Steel Processing and Products, Central Iron and Steel Research Institute, Beijing 100081, China
²National Engineering Research Center of Continuous Casting Technology, Central Iron and Steel Research Institute, Beijing 100081, China
³Research Institute of Special Steel, Central Iron and Steel Research Institute, Beijing 100081, China

The texture of high permeability grain-oriented silicon steel produced by Thin Slab Casting and Rolling process through adopting low slab reheate temperature and AlN as the main inhibitor has been studied. The results show that the microstructure of the cold rolled strip is nonuniform through the thickness, and the Goss texture with a maximum intensity mainly concentrated on the surface. The microstructure of the normalized strip is fully recrystallized, and the Goss texture is in both the surface and the subsurface layer, with a maximum intensity in subsurface layer.

Keywords: high permeability grain-oriented silicon steel, microstructure, Goss texture, γ-fibre texture

1. Introduction

Grain-oriented silicon steel is an important magnetic material that is widely used as a core material in transformers, and it is the only product manufactured in the steel industry that applies the secondary recrystallization. The most successful texture control has been achieved in the mass production. Its magnetic properties, low core loss and high permeability, along the rolling direction, are closely related to the secondary recrystallization texture, i.e., the sharpness of [110]〈001〉 (Goss texture). Much research has been done on the development of Goss texture, but until now, researchers have not come to an agreement.

Thin Slab Casting and Rolling (TSCR) process is a new manufacturing technique. It is one of the most modern and competitive processes for the production of ultra thin strip, and the slab heating temperature with TSCR technology is only 1150°C. So more and more scholars focus the research on the grain-oriented silicon steel with TSCR technology now. The purpose of this study is to investigate the evolution of texture in high permeability grain-oriented silicon steel produced by TSCR process.

2. Experimental

Table 1 shows the chemical composition of the specimen. The steel was melted by vacuum induction furnace, and then poured into water-cooled copper mold with a dimension of 50 mm × 100 mm × 400 mm. The temperature of the slab should be no less than 950°C before we remove the slab from the mold. In the subsequent process, the slab was kept at 1150°C for 0.5 h in a holding furnace, and then hot rolled to 2.3 mm thick strip. Next the hot rolled strip was normalized, the strip was heated to 1120°C at first and then air-cooled to 900°C, the times under these temperatures are 3.5 and 2 min respectively, then water quenched. Subsequently, the normalized strip was rolled to 0.3 mm by single-stage cold rolling. Finally, the specimen was subjected to decarburization annealing in wet hydrogen at 875°C and high temperature annealing at 1200°C. The final Iron loss is 1.231 W/kg, magnetic induction is 1.908 T.

The texture at different stages is analyzed by ZEISS SUPRA 55VP SEM with EBSD system. The sample surface was sanded with granularity 100 eye sanding paper from 200 eye to 1500 eye, and ensure there is no scratch on the surface, then the electropolishing was done. Before the scanning, we should make sure that the confidence index (CI) value of the selected area is above 0.8 and also the smallest grain size be calculated. The scanning step was set as one third of the smallest grain size. With these, three regions were scanned in each sample and the combined data of these three regions can be used to analyse the texture of the sample.

3. Results and Discussion

3.1 Evolution of microstructure

Figure 1 shows the microstructure of hot rolled strip, we can see that the microstructure is non uniform along the direction of thickness. It can be divided into three parts: surface layer, transition layer, and core layer. Recrystallization microstructure can be seen on the surface and the grain size is about 10–50 µm. The transition layer is a deformed microstructure with the grains elongated along the rolling direction. We also can see that the core layer is non-recrystallization deformed microstructure.

The microstructure of normalized strip was shown in Fig. 2. Compared with hot rolled strip, the grains are obviously coarsened in both the surface and the subsurface layer, the grain size is about 20–100 µm. Recrystallization can be observed in the core layer with the grain size is 50–200 µm.

Figure 3 shows the microstructure of cold rolled strip, the recrystallization microstructure of normalized strip transformed into fibrous tissues after one-stage heavy reduction rate cold-rolling.
Figure 4 shows the microstructure of decarburization annealed sheet. From it we can see that the microstructure of cold rolled strip transformed into primary recrystallization, the grain size is 10–30 µm, and the average grain size is 18 µm.

Figure 5 shows the abnormal growth Goss grains. The grain boundary is uneven, and grain size is nonhomogeneous, about 6–60 mm.

### 3.2 Evolution of Goss texture

Figure 6 shows the ODFs for the $\varphi_2 = 45^\circ$ section at different thickness in the hot rolled strip, which illustrates the main texture components and their intensity. In surface layer ($S = 0$), the hot rolled strip has a significant intensity in the general vicinity of Goss texture with the maximum intensity at the exact Goss orientation of $\approx 2.63$. Furthermore, there are $\{554\}<225>$, $\{332\}<113>$ and some $\alpha$-fibre texture in the surface layer. In subsurface layer ($S = 1/4$), Goss texture was transformed into $\gamma$-fibre texture with the increase of thickness, and the intensity of $\alpha$-fibre texture is higher than that of the surface layer, and the orientation intensity increases to 8.062. In center layer ($S = 1/2$), a strong $\{001\}<110>$, i.e., rotated cube texture, is observed. The maximum intensity of texture is 15.208. Therefore, Goss texture is mainly distributed in the surface layer of the hot rolled strip.

Table 1 Chemical composition of specimen (mass%).

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Carbon</th>
<th>Silicon</th>
<th>Manganese</th>
<th>Copper</th>
<th>Sulphur</th>
<th>Acid-soluble Alcohol</th>
<th>Aluminium</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi-B</td>
<td>0.04</td>
<td>3.00</td>
<td>0.1</td>
<td>0.15</td>
<td>0.0045</td>
<td>0.03</td>
<td>0.011</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 1 Microstructure of hot rolled strip (a) Cross section (b) Vertical section.

Fig. 2 Microstructure of normalized strip (a) Cross section (b) Vertical section.

Fig. 3 Microstructure of cold rolled strip.

Fig. 4 Microstructure of decarburization annealed sheet.

Fig. 5 Abnormal growth Goss grains.
Fig. 6 ODFs section of $\varphi_2 = 45^\circ$ at the different thickness in hot rolled strip.

Fig. 7 ODFs section of $\varphi_2 = 45^\circ$ at the different thickness in normalized strip.

Fig. 8 ODFs section of $\varphi_2 = 45^\circ$ at the different thickness in cold rolled strip.

Fig. 9 ODFs section of $\varphi_2 = 45^\circ$ at the different thickness in decarburization annealed sheet.

Fig. 10 ODF section of $\varphi_2 = 45^\circ$ in final product.

Fig. 11 Area percentage of [110](001) at different stages.
Figure 7 shows the ODFs for the $\phi_2 = 45^\circ$ section at different thickness in the normalized strip, similar to Fig. 6, it shows the main texture and their intensity. In the surface layer ($S = 0$), the normalized strip has a significant intensity in the general vicinity of Goss texture with a maximum intensity at the exact Goss orientation of $\sim 3.922$, which is higher than that of the hot rolled strip. Furthermore, there is some $\gamma$-fibre texture, such as $\{111\}\{112\}$. In the subsurface layer ($S = 1/4$), the Goss texture is still the strongest texture, and the orientation intensity of Goss texture increases to 4.923, which is higher than that of the surface layer. In the center layer ($S = 1/2$), a strong $\{001\}\{110\}$, i.e., rotated cube texture, is observed, and the maximum intensity of texture is 4.194, which is lower than that of the hot rolled strip.

Figure 8 shows the ODFs for the $\phi_2 = 45^\circ$ section in the cold rolled strip. In surface layer ($S = 0$), the cold rolled strip has a significant intensity in the general vicinity of $\gamma$-fibre texture, and it is the typical cold rolled texture in both the subsurface layer and the center layer, with the $\{223\}\{110\}$ being the main texture. Meanwhile Fig. 9 presents the ODFs for the $\phi_2 = 45^\circ$ section in the decarburization annealed sheet. The cold rolled strip was completely recrystallized after being decarburization annealed, and the texture changed accordingly. The $\gamma$-fibre texture became the main texture, such as the $\{111\}\{112\}$. Figure 10 shows the ODF in the final product texture. It is the single Goss texture, and the intensity reached 161.202.

3.3 Discussion

It is a well-known fact that the Goss orientation grains, in primary recrystallization, are derived from the Goss orientation grains of the surface layer of hot rolled strip, which is the so-called “texture genetic effects". So the hot rolled strip should include two characteristics: (1) there are accurate $\{110\}\{001\}$ grains in the surface layer. These grains will be remained in the deformation bands during the following cold rolled process, and it as the Goss nucleus of primary recrystallization. The importance of Goss orientation grains in the surface layer of hot rolled strip was studied by Bottcher,17,18 The surface of hot rolled strip was exfoliated from one side and two sides, respectively. The result shows that it had no effect on secondary recrystallization when exfoliation from one side, but the secondary recrystallization did not occur when exfoliation from two sides. (2) There is strong $\{111\}\{112\}$ orientation in the hot rolled strip. There are the most deformation bands in $\{111\}\{112\}$ orientation grains, and Goss orientation grains will be remained in the deformation bands during the following cold rolling process as previously mentioned. So the more $\{111\}\{112\}$ orientation grains, the more Goss nucleus.

Hence, inhomogeneity of the recrystallization in hot rolled strip, especially Goss texture intensity of surface layer and subsurface layer, is crucial to the perfect development of secondary recrystallization. The texture of surface layer in hot rolled strip is mainly Goss texture, which is the type desired. However, the intensity of Goss texture is almost 0 in both subsurface and intermediate layer. But in subsurface layer, $\{111\}\{112\}$ is the main texture, which is the favorable texture. The specimen have a strong cubic texture in center layer of hot rolled strip, which is detrimental to the development of secondary recrystallization.

After normalized, the main texture in surface layer is still the Goss texture and the orientation intensity has a substantial increase, compared to the hot rolled strip. More importantly, there is also strong Goss texture existing in subsurface layer ($S = 1/4$). So Goss texture distributes in both the surface layer and subsurface layer, thus having more potential for Goss nucleation sites.

After cold rolled, the main texture is $\{223\}\{110\}$. During cold rolling process, the texture on surface and subsurface layer ($S = 0–1/4$) rotated in the following way:

$$
\{110\}\{001\} \rightarrow \{554\}\{225\} \rightarrow \{111\}\{112\} \\
\rightarrow \{111\}\{110\} \rightarrow \{223\}\{110\}.
$$

While the texture in center layer rotated as:

$$
\{001\}\{110\} \rightarrow \{112\}\{110\} \rightarrow \{223\}\{110\}.
$$

So the cold rolled texture of high permeability grain-oriented silicon steel is the typical cold-rolled texture.

The texture further rotated after decarburization annealed, but the rotate path is contrary to cold rolling process. The rotated path is: $\{223\}\{110\} \rightarrow \{111\}\{110\} \rightarrow \{111\}\{112\}$. So it is mainly the $\gamma$-fibre texture. The final product texture is only Goss texture after high temperature annealing process.

From above analysis, it is manifested that Goss texture can be found in surface layer of hot rolled strip, but the orientation density is low. After normalized, the Goss texture can be found in both the surface and subsurface layer, and the orientation density of the Goss texture also has a corresponding increase. After decarburization annealed, it is mainly the $\gamma$-fibre texture, which is beneficial to the development of secondary recrystallization.

Figure 11 shows the area percentage of $\{110\}\{001\}$ at different stages. It was found that the $\{110\}\{001\}$ texture exists in both surface ($S = 0$) and subsurface layer ($S = 1/4$) of hot rolled strip, and $\{110\}\{001\}$ texture exists in the full thickness of the normalized strip, but it only exists in the surface layer of cold rolled strip and decarburization annealed sheet. Although the maximum content of Goss texture was obtained in subsurface layer of normalized strip, it disappeared after cold rolling. So only the Goss texture in the surface layer was preserved during production process. To some extent it verified the importance of Goss orientation grains in the surface layer of hot rolled strip.

4. Conclusion

(1) In the hot rolled strip, the microstructure is non uniform along the direction of thickness, and it is mainly the Goss texture, with a maximum intensity in the surface. In subsurface layer, it is the $\gamma$-fibre and $\alpha$-fibre texture; In the center layer, it is mainly the $\alpha$-fibre texture;

(2) In the normalized strip, the microstructure is fully recrystallized, and it is mainly the Goss texture in both the surface and subsurface layer, with a maximum intensity in subsurface layer. In the center layer, it is mainly the $\alpha$-fibre texture.
(3) In the cold rolled strip, the microstructure is fibrous tissues, and it is the typical cold-rolled texture, with the $(223)(110)$ being the main texture.

(4) In the decarburization annealed sheet, the microstructure is fully primary recrystallized, and the $\gamma$-fibre texture is the main texture.

(5) In the final product, it is the single Goss texture, and the intensity reached to 161.202.

Acknowledgements
The research was financially supported by the National Natural Science Foundation of China (50934009).

REFERENCES