1. Introduction

Thin-gauge, non-oriented electrical steels (NOES) have been extensively utilized to fabricate cores for the generators and motors of next-generation energy vehicles [1]. The research on thin-gauge NOES has mostly concentrated on their low iron losses, particularly at high frequencies [2]. NOES are primarily produced using the one-stage cold rolling method during conventional processes, which includes casting, hot rolling, normalizing annealing, cold rolling, and final annealing [3]. The magnetic properties of NOES are affected by many factors, such as the texture, grain size, final sheet thickness, and chemical composition [4, 5]. The microstructure, texture, and magnetic properties of the final sheet depend to a large extent on the rolling process and subsequent heat treatment. Currently, normalizing annealing is an important technical method to improve the texture and microstructure of NOES [6]. The ideal crystallographic texture is the $\gamma$-fiber ($\{100\} // \text{ND}$, normal direction) texture, while the most deleterious texture is the $\alpha$-fiber ($\{111\} // \text{ND}$) texture in NOES [7, 8]. However, during conventional production processes, the $\gamma$-oriented grains in NOES preferentially recrystallize during the final annealing treatment. Then, the $\gamma$-oriented grains develop by consuming other grains such as $\alpha$-oriented ($\{110\} // \text{RD}$, rolling direction) and $\lambda$-oriented grains, which is related to the different stored strain energies of grains with different orientations [9, 10]. Hence, it is generally difficult to decrease the harmful $\{111\} // \text{ND}$ texture and increase the favorable $\{100\} // \text{ND}$ texture in the final annealed texture. Thin-gauge NOES usually undergo heavy cold-rolling reduction, resulting in texture deterioration, which decreases the magnetic induction. Thus, it is critical to overcome the tradeoff between magnetic induction and high-frequency iron loss by improving the recrystallized texture and microstructure of thin-gauge annealed sheets [11].

Recently, it has been reported that the annealing texture of final sheets can be improved by increasing the hot-band grain size, which increases the magnetic induction and also reduces the core loss in NOES [12].
Cunha et al [13] demonstrated that normalization can greatly improve the magnetic properties by enhancing the Goss ($\{110\} \langle 001 \rangle$) texture in the final annealed sheets. Normalization not only homogenizes and coarsens hot-band microstructures, but it also produces more shear bands during subsequent cold-rolling. During final annealing, Goss-oriented grains easily nucleate within the shear bands and provide more nucleation sites. Furthermore, the effect of normalization on the iron loss also shows that the grain size of the final sheets increases upon increasing the grain size of hot-rolled sheets, which decreases the iron loss [14, 15]. However, the texture that is present before cold rolling also affects the final annealed texture and thereby affects the magnetic properties of the final sheets.

Therefore, methods to obtain an ideal final microstructure and texture by optimizing the microstructure and texture of hot-rolled sheets have become a research hotspot [16]. The above-mentioned studies have all focused on increasing the grain size before cold rolling by increasing the normalizing temperature to enhance the magnetic properties of the final annealed sheets; however, little research has focused on the effect of the normalizing texture on the final magnetic properties. In our previous study, strong $\{100\} \langle 012 \rangle - \{411\} \langle 148 \rangle$ textures were obtained by increasing the normalization temperature and holding time, which improved the magnetic properties of the final annealed sheets [17]. Based on the optimized recrystallization texture, it is necessary to further shorten the normalizing time in consideration of actual industrial production needs. In this study, 0.3-mm-thick thin-gauge NOES were processed by one-stage cold rolling with different normalizing time. The effect of the grain size before cold rolling on the magnetic properties of thin-gauge NOES was studied.

2. Experimental

A 230 mm-thick continuous casting billet was heated at 1150 °C, then hot-rolled to a thickness of 2.1 mm. The chemical composition (wt.%) of the billet was Si 3.0, Al 0.85, C 0.002, Mn 0.33, N 0.002, and S 0.003. The hot-rolled sheets underwent normalizing in a 100% N₂ atmosphere at 1000 °C for 1, 3, 5, and 15 min, respectively. Subsequently, all normalized sheets were cold-rolled to a thickness of 0.3 mm by the one-stage method. Finally, the 0.3 mm-thick cold-rolled sheets were annealed at 1000 °C for 2 min in a 75% H₂ and 25% N₂ mixed atmosphere to obtain the final annealed sheets. To study the texture evolution during cold-rolling and subsequent annealing, the 2.1-mm-thick hot-rolled sheets normalized for 15 min were cold-rolled to thicknesses of 1.66, 1.13, and 0.78 mm. In addition, the 0.3 mm cold-rolled sheets with different normalizing time were annealed at 750 °C for 25, 75, and 180 s to obtain partially and completely recrystallized samples.

A Zeiss optical microscope was used to characterize the microstructures. The textures were measured by an electron backscatter diffraction (HKL-Channel 5) system equipped on a Zeiss ΣIGMA scanning electron microscope. An electrical steel tester (MPG 200D) was used to measure the magnetic induction $B_{r0}$ (determined at 5000 A m⁻¹) and the core loss $P_{1.5/50}$ ($P_{1.5/50}$ determined at 1.5 T, 50 Hz), $P_{1.0/400}$ ($P_{1.0/400}$ determined at 1.0 T, 400 Hz) of the final annealed sheets. The single-sheet test samples were sheared to 30 mm × 300 mm along the transverse direction (TD) and rolling direction (RD).

3. Results and discussion

3.1. Evolution of microstructure and texture during normalizing

The microstructure of hot-rolled sheets contained inhomogeneities because heavily rolling reduction easily produced unevenness along the thickness of the steel plate as shown in figure 1(a). The surface layer consisted of fine recrystallized grains, the sub-surface layer consisted of deformed grains and partially-recrystallized grains, and the middle layer consisted of deformed grains. After normalization at 1000 °C, the fibrous microstructure disappeared, and the hot-rolled sheet was completely recrystallized. As shown in figures 1(b)–(e), the average grain sizes of the different normalized sheets were 88, 133, 189, and 290 μm, respectively.

Figure 2 shows the inverse pole figure (IPF) maps and corresponding to the $\varphi_2 = 45^\circ$ section of the orientation distribution function (ODF) of the hot-rolled sheet and sheets normalized for different time. Figure 2(f) indicates that the dominant textures were strong $\{100\} \langle 011 \rangle - \{112\} \langle 110 \rangle$ and weak $\gamma$-fibers in the hot-rolled sheet. After normalization for 1 min, the dominant texture components were $\{100\} \langle 011 \rangle$ and $\{114\} \langle 110 \rangle$, and a weak Goss texture. After normalization for 3 min, the dominant texture components were $\{100\} \langle 012 \rangle$ and $\{411\} \langle 148 \rangle$. As the normalizing time increased to 5 and 15 min, the $\{411\} \langle 148 \rangle$ textures became much stronger than in other normalized sheets. There are also some unfavorable $\gamma$-oriented grains in the normalized sheets, whose volume fraction in the sample normalized for 1 min was 8.93%. As the normalizing time increased to 3, 5, and 15 min, the volume fraction of $\gamma$-oriented grains decreased to 5.47%, 6.22%, and 5.59%. Based on a previous study, the main reason for the selective growth of $\{411\} \langle 148 \rangle$ oriented grains was the high boundary mobility and the size advantages of hot-rolled sheets in non-oriented electrical steel [17].
3.2. Evolution of the microstructure and texture during cold rolling

The deformation microstructures of 0.3-mm-thick cold-rolled sheets with different normalizing time are shown in figure 3. The deformation microstructure consists of elongated grains and shear bands after heavy cold-rolling reduction. When the normalizing time was 1 min, the deformation microstructure was fibrous, and the heavy reduction rate caused some of the shear bands to flatten and straighten, and only a small part of the shear bands could be observed. Large grains have weaker strain compatibility than small grains during plastic deformation. As a result, the homogeneous deformation of large grains is more hindered than that of small grains under similar deformation conditions, which promotes the formation of more shear bands in samples with large grain sizes [18, 19]. As the normalization time increased, the shear band density in the obtained cold-rolled sheets also increased, and the morphology of the shear bands also increased upon increasing the grain size of the normalized sheets; however, when the normalization time increased to 15 min, the shear band distribution became very uneven.

Ferrite steels usually form similar rolling textures during cold rolling, including \{100\}〈011〉, \{112\}〈110〉, \{111\}〈110〉, and \{111\}〈112〉 texture components [20]. The IPF maps and \(\phi_2 = 45^\circ\) section ODF of cold-rolled sheets with different normalizing time are shown in figure 4. After cold rolling and heavy reduction, the deformation texture components were \{100\}〈011〉—\{112\}〈110〉 and \{111\}〈110〉, respectively; however, there
Figure 3. Optical microscopy image of the microstructure of cold-rolled sheets with different normalizing time (four samples are superimposed): (a) 1 min; (b) 3 min; (c) 5 min; (d) 15 min.

Figure 4. The IPF maps and $\varphi_2 = 45^\circ$ section ODF of cold-rolled sheets with different normalizing time: (a), (e) 1 min; (b), (f) 3 min; (c), (g) 5 min; (d), (h) 15 min.
were also some differences in the texture intensity and distribution. The orientation of \(\{223\}\{110\}\) and \(\{111\}\{110\}\) texture was the strongest, and the orientation of \(\{100\}\{011\}\) was also present, with a strong peak value of the cold-rolled sheet obtained in the sample normalized for 1 min. In the sample normalized for 3 min, the intensity of \(\{100\}\{011\}\) component and the \(\gamma\)-texture decreased, while the intensity of the \(\{112\}\{110\}\) texture increased. When the normalizing time was increased to 5 min and 15 min, the intensity of the \(\{100\}\{011\}\) textures was higher than the sample normalized for 3 min, and the \(\gamma\) texture continuously decreased. As the normalizing time increased, the intensity of the \(\gamma\) texture greatly decreased in cold-rolled sheets. The cold rolling texture is an important factor that affects the recrystallization texture in the subsequent final annealing process.

Since the \(\{411\}\{148\}\) texture is the main texture in the normalized sheets, it is necessary to study the strong \(\{411\}\{148\}\) texture evolution during cold-rolling. Figure 5 shows the samples normalized for 15 min and cold-rolled at: (a), (e) 21%; (b), (f) 42%; (c), (g) 63%; (d) Typical texture in the \(\varphi_2 = 45^\circ\) section ODF and texture rotation path.

**Figure 5.** The IPF maps and \(\varphi_2 = 45^\circ\) section ODF of sheets corresponding to the sample normalized for 15 min and cold-rolled at: (a), (e) 21%; (b), (f) 42%; (c), (g) 63%; (d) Typical texture in the \(\varphi_2 = 45^\circ\) section ODF and texture rotation path.
the {λ} texture component decreased from 23.5% to 17.4%. In the final annealed sheets, the main annealing textures of the normalized sheets observed an orientation transition from {113} to {112} in some grains as the cold rolling reduction rate increased to 90%.

### 3.3. Texture evolution during final annealing

Figures 6(a)–(d) shows the IPF maps of the final annealed sheets obtained with different normalizing time. According to the EBSD statistics, the average grain sizes were 51, 60, 68, and 80 μm in the final annealed sheets with different normalizing time. Normalized sheets with smaller grain sizes have a higher stored energy due to cold-rolling deformation, so the nucleation rate increased during annealing, leading to a small grain size in the final annealed sheets. Meanwhile, the number of nucleation sites also increased with the number of original grain boundaries in the normalized sheets. Figures 6(e)–(h) shows the ODF maps corresponding to the {φ2 = 45°} and {φ2 = 0°} sections of the final annealed sheets. The main annealing textures of the final sheets were strong λ fiber, α′ fiber, γ fiber, and weak η fiber (RD) textures. Table 1 shows the volume fractions of the different texture components in the final annealed sheets obtained with different normalizing time. The results indicate changes in the {100}, {411}, {110} texture components. In the final annealed sheet of the sample normalized for 1 min, strong {111} and {223} textures were observed, and there was also a weak {100} texture belonging to a λ texture, whose volume fraction was only 4.3%. When the final annealed sheet of the sample was normalized for 3 min, the texture component was dominated by {111} and {411} textures. The volume fractions of the {100} and {210} textures increased to 9.8% and 4.7% as the normalizing time increased, and the volume fraction of the {111} texture component decreased from 23.5% to 17.4%. In the final annealed sheet of the samples normalized for 5 min and 15 min, the texture was dominated by {100} and {111}.

![Figure 6](image-url)
volume fraction of the increased slightly. The final annealed sheets were closely related to the inherited recrystallized grains that nucleated at grain boundaries. Considering the evolution of the recrystallized grains during recrystallization annealing, the undistorted subcrystalline microstructure of the deformed matrix gradually coarsens and grows to engulf and consume the surrounding deformed matrix. Some low-angle grain boundaries transform to high-angle grain boundaries via dislocation climbing and polygonization. The IPF maps and texture component figures of partially recrystallized samples annealed at 750 °C for 25 s corresponding to the sample normalized for (a), (b) 3 min; (c), (d) 5 min; (e), (f) 15 min.

Figure 7. The IPF maps and texture component figures of partially recrystallized samples annealed at 750 °C for 25 s corresponding to the sample normalized for (a), (b) 3 min; (c), (d) 5 min; (e), (f) 15 min.

The strong (100) (013) texture in the final annealed sheets was attributed to the enhancement of the (411) (148) texture and coarse grains in the normalized sheet. However, when the normalizing time was 15 min, the volume fraction of the (100) (013) texture component slightly decreased, while the (411) (148) texture increased slightly. The (411) (148) texture was also the stable final annealing texture after heavy cold rolling reduction, which was closely related to the inherited recrystallized (411) (148) texture in the normalized sheet. The intensity of the γ texture in the final annealed sheet decreased continuously with increase of the normalizing time because the number of grain boundaries that provided nucleation sites for γ-oriented grains decreased due to an increased grain size before cold rolling.

3.4. Nucleation of (100) (013) grains during recrystallization annealing

The IPF maps and texture component figures of partially recrystallized samples are shown in figure 7. During recrystallization, the undistorted subcrystalline microstructure of the deformed matrix gradually coarsens and grows to engulf and consume the surrounding deformed matrix [25]. Some low-angle grain boundaries transform to high-angle grain boundaries via dislocation climbing and polygonization [24]. The new crystal nuclei were mainly concentrated in high deformation energy storage regions where dislocations were relatively concentrated, such as shear bands and grain boundaries. Some (100) (013) and (411) (148) oriented grains nucleated in (112) (110) deformed grain boundaries at the early stage of recrystallization, as shown in figure 7(b). Moreover, many Goss and some (210) (001) recrystallized grains nucleated in the shear bands with (111) (112) orientations, and a small portion of (100) (013) grains also nucleated in the (111) (112) shear band, as shown in the A region of figure 7(d). The (100) (013) grains that nucleated in shear bands and grain boundary were especially prominent in regions B, D, and F of figures 7(d), (f). The (100) (013) grains preferentially nucleate at (112) (110) shear bands and (112) (110)−(100) (011) grain boundaries. Meanwhile, (411) (148) grains also nucleated at (100) (011) grain boundaries, as shown in regions C and E of figures 7(b), (d). The (100) (013) and (411) (148) grains are more likely to nucleate at the deformed (100) (110) grain boundaries during the late recrystallization stage, as shown in regions A and B of figure 8(b). Homma et al. [25, 26] also reported that (411) (148) oriented grains nucleated near (100) (011)−(112) (110) α-fiber deformed grain boundaries.

Figures 8(c)–(f) shows the misorientation relationship between (100) (013) and (411) (148) grains and the adjacent deformed grains. Considering the evolution of the final annealed texture, it is necessary to investigate...
the misorientation relationship between the newly-nucleated \{100\} (013) oriented grains and their neighboring deformed grains. The fast-growing \{100\} (013) grains mostly have 37.8° [111] misorientations with respect to other \{112\} (110) deformed grains. This misorientation is very close to Σ7 grain boundaries (38.21° [111]), which have high mobility [27], which promotes the growth of \{100\} (013) oriented grains. The formation of the \{100\} (013) texture is attributed to the oriented growth mechanism. Furthermore, the misorientation between the \{100\} (013) oriented grains and \{100\} (011) oriented deformed grains was 24.3° [001]. Usually, 20°–45° misorientations with respect to \{112\} (110) boundaries are called high-mobility grain boundaries [28]; thus, the \{100\} (013) grains formed high-mobility grain boundaries within the deformed matrix of \{112\} (110)–\{100\} (011).

Similarly, as another stable recrystallization texture obtained in the final sheets, it is also important to analyze the changes of the \{411\} (148) texture. Figures 8(e), (f) shows that the misorientation relationship between \{411\} (148) oriented grains and \{100\} (011) oriented deformed grains is 22.3° [4–30]. The misorientation between the \{100\} (011) and \{411\} (148) grains is 26.8° [3–32], which is very similar to the Σ13b grain boundaries (27.8° [111]). This kind of grain boundary is also considered to have a high mobility in BCC metals [27, 29]; therefore, \{411\} (148) orientated grains have high-mobility grain boundary within the deformed matrix of \{100\} (011).

Figure 8(g) shows the IPF maps of the cold-rolled sheet corresponding to normalized for 5 min and annealed at 750 °C for 180 s. The results indicate that recrystallization was nearly completed, and the dominant recrystallization textures were \{100\} (013) and \{111\} (112). According to EBSD statistics, the average grain size of all grains was 14 μm, and the average grain sizes of \{100\} (013), \{411\} (148) and \{111\} (112) oriented grains were 19.1, 14.4, and 14.7 μm, in which the \{100\} (013) oriented grains have a much larger size than the others. The main reason for the formation of a strong \{100\} (013) texture was the high mobility and the larger grain size in the low stored energy matrix. Therefore, oriented growth mechanisms contributed to the dominant \{100\} (013) grains in annealed samples. At the same time, \{111\} (uvw) oriented grains nucleate preferentially in grain boundaries and in the deformed matrix with a \{111\} (uvw) orientation [30, 31]. It can also be observed in figure 7 that a large number of \{111\} (112) oriented recrystallized grains nucleated at the grain boundary. As recrystallization proceeded, the \{111\} (112) oriented grains consumed grains with other orientations and deformed matrixes due to its quantity advantage, so the \{111\} (112) orientation in the γ texture was also stronger after complete recrystallization. Goss-oriented grains nucleated and tended to form earlier in shear bands as shown in figure 7(b), but they did not appear any larger than grains with other orientations in figure 8(h).
A parameter can affect the hysteresis loss, the lower parameter, which is the minimum angle between the direction of the applied magnetic field and the closest (100) direction of the crystal. The relationship between the texture component and A* parameter is shown in the literature [32, 33]. D represents the average grain size of final annealed sheet. The grain size and Si content will also affect B_{50}. In this work, D and Si are assumed to be 68 μm and 3. The B_{50} values calculated by equation (1) are shown in Table 2. The low values of A* correspond to a higher B_{50} value.

The A* parameter of the {411} / {148} texture studied in final annealed sheet was lower than that of the {111} / {112} texture, which have higher B_{50} values. Compared with the {111} / {112} texture, the {411} / {148} texture is more beneficial to the magnetic properties, in agreement with Zu et al [34, 35]. In this work, the {411} / {148} texture did not have a remarkably positive effect on the magnetic properties of the final annealed sheet compared with the {100} / {013} and {210} / {001} textures. Since it is a common texture in the final annealed sheets, it is hoped that the strengthening {411} / {148} texture can weaken the {111} / {112} texture. At the same time, the A* parameter can affect the hysteresis loss, the lower A* parameter value means lower hysteresis loss [33]. The grain size also has an important effect on the iron loss, and increasing the grain size of final annealed sheet can effectively reduce the hysteresis loss [19]. The B_{50} values were much higher, while the P_{1.5/50} and P_{10/400} values simultaneously decreased upon increasing the normalizing time. The final sheet sample obtained after being normalized for 5 min had the highest magnetic induction (1.714 T), which was due to the strong {100} / {013} and {210} / {001} textures and the weak {111} / {112} texture; thus, appropriately increasing the normalizing time can greatly increase the magnetic induction. After the normalizing time further increased to 15 min, the magnetic induction decreased slightly due to a decrease in the {100} / {013} and {210} / {001} texture components, as well as the slightly worse uniformity of the final grain size. In addition, the lower core losses with 2.394 W kg\(^{-1}\) (P_{1.5/50}) and 15.510 W kg\(^{-1}\) (P_{10/400}) were obtained because the larger grain size and weaker γ texture reduced the hysteresis loss, which caused low core losses in the final annealed sheets.

Therefore, grains with other orientations that have a growth advantage might have consumed the Goss-oriented grains, which is why the Goss component became very weak after annealing.

### 3.5. Magnetic properties of final annealed sheets

The microstructures of final annealed sheets are shown in figure 6, and the corresponding magnetic properties are shown in figure 9. The relationship between texture content and magnetic properties is explained by the following empirical equation [32, 33]:

\[
B_{50} = 2.19 - 0.013A^* - \frac{0.27}{D} - 0.03Si
\]  

(1)

Different texture components may cause anisotropic magnetic properties, which can be described by A* parameter, which is the minimum angle between the direction of the applied field and the closest (100) direction of the crystal. The relationship between the texture component and A* parameter is shown in the literature [32]. D represents the average grain size of final annealed sheet. The grain size and Si content will also affect B_{50}. In this work, D and Si are assumed to be 68 μm and 3. The B_{50} values calculated by equation (1) are shown in Table 2. The low values of A* correspond to a higher B_{50} value.

| Single texture | A* (°) | B_{50} (T) |
|----------------|-------|------------|
| {100} / {013}  | 22.50 | 1.803      |
| {210} / {001}  | 27.88 | 1.734      |
| {411} / {148}  | 30.77 | 1.696      |
| {111} / {112}  | 38.68 | 1.593      |
| {111} / {110}  | 38.68 | 1.593      |

Figure 9. Magnetic induction B_{50} (a), and iron loss P_{1.5/50} - P_{10/400} (b) of the final annealed sheets.

Table 2. Calculated B_{50} for an ideal single texture by equation (1).
4. Conclusion

1. After cold rolling, the initial \{411\}\{148\} texture transformed to \{114\}\{110\} and \{311\}\{136\} textures, and as the rolling reduction increased, the \{311\}\{136\} texture rotated toward a \{112\}\{110\} texture, but not toward a \{111\}\{112\} texture.

2. The normalized sheets with large grains resulted in the formation of more shear bands during cold rolling, which provided more nucleation sites for \{100\}\{013\} oriented grains. The nucleation sites for \{100\}\{013\} grains were located at the \{112\}\{110\} and \{100\}\{011\} deformed grain boundaries, and in the \{112\}\{110\} and \{111\}\{112\} oriented shear bands. Strong \{100\}\{013\} textures formed due to the high mobility and large grain size.

3. As the normalizing time increased, the magnetic properties were greatly improved in the final annealed sheets. The superior magnetic inductions were due to the strong \{100\}\{013\} and \{210\}\{001\} textures and the weak \{111\}\{112\} texture. The larger grain size and weaker γ texture reduced the hysteresis loss, which caused low core losses in the final annealed sheets.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.1016/j.matlet.2019.126844

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