1. Introduction

High silicon steels (Si ≥ 4.5 wt%) produced using warm rolling have become interesting materials for power electronics applications, such as the choke coil, transformer, motor and magnetic shield, because they exhibit excellent soft magnetic properties in high frequency.1–3) However, a too high Si content results in the formation of high-britleness B2 (FeSi) and DO₃ (Fe₃Si) ordered phases in high silicon steels.4–7)

Recently, with attention focused on texture evolution of electrical steels, adding rare earth (RE) elements has been employed as an effective way to improve the magnetic properties of steels. Shi et al.8) revealed that an addition of La in the electrical steel affected the texture evolution and grain size by coarsening inclusion size. Li et al.9) found that Ce₂O₂S inclusions in Fe–6.5 wt% Si Ce-doped alloy could promote the heterogeneous nucleation of grains during twin-roll casting. However, there is limited reliable and detailed information to understand the role of Y addition on the texture evolution of silicon steels.

The objective of current study is to identify the effects of Y on inclusion and texture evolution, which is important not only for optimizing alloy composition but also for improving soft magnetic properties of Fe–6.9 wt%Si alloy.

2. Experiments

The experimental steels were prepared using a 45 kg high frequency vacuum furnace and forged into slabs with dimensions of 50 (thickness) × 120 (width) × 200 (length) mm. The chemical compositions of experimental steels were presented in Table 1. The ingots were forged into slabs with 50 mm thickness at 1 180 °C, hot-rolled to 2.5 mm thickness in the temperature range from 1 090 °C to 880 °C by 10 passes on a reversal hot rolling mill, warm rolled to 0.5 mm at 700 °C after acid picking. The pass reductions of warm rolling passes were 0.06–0.08 mm in the case of roll mill speed at 0.06 m/s, and then they were reheated for 2–4 minutes in the box-type furnace after each pass. Then all warm-rolled sheets were annealed at 920 °C for 10 min in a Nitrogen atmosphere.

The element distribution of inclusions was investigated...
using Electron probe micro-analysis (EPMA) at a current of $1.05 \times 10^{-8}$ A and an operating voltage of 20 kV. Leica DM 2500M optical microscope (OM) and FEI Quanta 600 scanning electron microscope (SEM) were conducted to investigate the microstructures of annealed samples along the longitudinal section. Micro-textures of warm-rolled sheets were obtained using electron backscattered diffraction (EBSD), and the normal direction and rolling direction were defined by ND and RD. Macro-textures were measured at different thickness layers defined by $S = 2a/d$ based on X-ray diffraction, where $d$ and $a$ represented the whole thickness and distance away from center layer. $S = 1.0$, $S = 0.5$ and $S = 0$ represented the surface layer, subsurface layer and center layer, respectively.

The magnetic properties of specimens with 100 mm (length)×30 mm (width) were conducted on a single sheet tester, and their magnetic inductions were measured at magnetic field density of 800 Am$^{-1}$ ($B_8$), and iron losses were determined at 1 T, 50 Hz ($P_{10/50}$), 1 T, 400 Hz ($P_{10/400}$), 1 T, 1 000 Hz ($P_{10/1 000}$).

3. Results and Discussion

3.1. Inclusion, Microstructure and Texture of Warm-Rolled Sheets

Figure 1 presents the EPMA elemental mappings of inclusions in warm-rolled sheets, and the mass concentration of each element can be distinguished using various colors and degree contrast. The size of larger-sized Al$_2$O$_3$ in non-Y-doped sample is about 5 μm, which is bigger than Y$_2$AlO$_3$ (1.2 μm) identified by the distribution of Al, O and Y elements in sample A2.

Figure 2 reveals the orientation images of warm-rolled sheets. Distinctly, some {110} (green) recrystallized grains preferentially form at {111} in-grain shear bands (white dotted line) as the preferential sites for nucleation, subsequently merge other adjacent orientation grains and grow up during warm rolling, and several recrystallization sites at inclusions

![Fig. 1. EPMA elemental mappings of inclusions in warm-rolled sheets: (a)–(c) Al$_2$O$_3$ in sample A1 and (d)–(g) Y$_2$AlO$_3$ in sample A2. (Online version in color.)](image-url)
are shown in white box (Fig. 2(a)). It is found that few recrystallized grains can be detected among the deformed ferrite grains (Fig. 2(b)).

**Figure 3** shows the microstructures of warm-rolled sheets observed by optical microscope. The ferrite grains are elongated along the deformation direction, and a great amount of inclusions occur at in-grain shear band.

The nucleation ability of ferrite grains on inclusions is related to the interface energy between inclusions and grain orientations based on the classical nucleation theory. Yang and Enomoto\(^{10}\) reported that \{100\} type interface had a maximum energy while a minimum interfacial energy occurred at \{110\} orientation. The inclusions and \{110\} recrystallized grains are connected in a matching way of
low interfacial energy, and the driving force required for the nucleation of \{110\} grains can be improved, thereby creating favorable conditions for the nucleation of \{110\} recrystallized grains at \{111\} in-grain shear bands. By contrast, the interface energy between inclusions and \{100\} grains is highest, which is not favourable for \{100\} grains nucleating at \{111\} in-grain shear bands.

Li et al.\(^{11}\) found \(\text{Y}_2\text{O}_3\) particles with coherent interface, and the interfacial energy was influenced by the lattice misfit. In contrast to coarsening \(\text{Y}_2\text{O}_3\) inclusions, the large difference of Young’s modulus between the matrix and fine \(\text{Y}_2\text{AlO}_3\) inclusions causes a decreasing interfacial energy. For this reason, after adding Y, the nucleation tendency of \{100\} grains is significantly increased in contrast to \{110\} grains nucleating at \{111\} in-grain shear bands, and the maximum interface energy between Y-inclusions and \{100\} grains possibly induces the grain growth of \{100\} grains (Fig. 2(b)).

During warm rolling, there are two recrystallization mechanisms such as \{110\} grains forming at \{111\} in-grain shear bands and \{110\} grains recrystallizing at inclusions. However, their contribution of recrystallization mechanisms is different for the improvement of \{110\} textures including \{110\} <001> Goss texture. In the case of constant rolling temperature and reduction during warm rolling, sample A1 and sample A2 have the same storage energy. Then there is a same effect on \{110\} grains forming at \{111\} in-grain shear bands, and it is inferred that, the nucleation of \{110\} recrystallized grains may be only determined by \{110\} recrystallized grains nucleating at \(\text{Al}_2\text{O}_3\) inclusions during warm rolling.

Figure 4 shows the through-thickness \(\phi_\parallel=45^\circ\) sections of ODF calculated by XRD in warm-rolled sheets. And apparently, non-Y-doped sample A1 exhibits strong \(\alpha\)-fiber (\(<1\overline{1}0>\parallel\text{RD}\)) and \(\gamma\)-fiber (\(<1\overline{1}1\overline{1}>\parallel\text{ND}\)) textures, as well as moderate \(\lambda\)-fiber (\(<001>\parallel\text{ND}\)) textures during warm rolling (Figs. 4(a)–4(c)). Notably, there is a significant increase in the intensity of \{110\} <001> Goss texture distributing in the subsurface layer (Fig. 4(b)) in contrast to the surface layer of sample A1. The intensities of \(\lambda\)-fiber textures on the center layer of sample A2 are obviously improved as compared to sample A1 (Fig. 4(c)), which may be attributed to the modifying effect of RE-oxide by means.
of Y doping (Fig. 4(f)).

3.2. Inclusion, Microstructure and Texture of Annealed Sheets

For the detailed investigation of recrystallization behavior, Fig. 5 presents the microstructures of annealed sheets observed by optical microscope. It is apparent from the figures that the size of recrystallized grains decreases due to Y addition.

Figure 6 reveals the microstructures of 920°C annealed sheets analyzed by SEM. It can be seen that the average grain size of annealed sheets decreases from 163 μm to 85 μm after adding rare earth Y.

RE elements can significantly reduce the interfacial tension of material and driving force of grain growth, hinder the corresponding atoms from liquid phase to solid phase due to a low equilibrium partition coefficient, inducing the deterioration of heterogeneous nuclei and inhibiting the grain growth during annealing.

Figure 7 presents the morphologies of inclusions in annealed sheets and EDS analysis. An irregular angular inclusion containing mostly O, Al, Fe elements exists in non-Y-doped sample A1, and the size of inclusion classified as Al2O3 is about 7 μm. Fine Y2AlO3 inclusion with a size

![Fig. 6. Microstructures of 920°C annealed sheets analyzed by SEM: (a) sample A1 and (b) sample A2.](image)

![Fig. 7. Morphologies of inclusions in annealed sheets and EDS analysis: (a) morphology of inclusion in sample A1; (b) EDS of inclusion in sample A1; (c) morphology of inclusion in sample A2 and (d) EDS of inclusion in sample A2.](image)
of 2.5 μm observed in Y-doped sample A2 can effectively affect the texture evolution.

Table 2 shows the size and number of inclusions in the steels. The results reveal a large variation in the average size and number of inclusions after adding Y. It is found that the average inclusion size of warm-rolled sheets decreases from 3.9 μm (without Y addition) to 1.4 μm (with 0.028 wt.% Y addition), while the number of inclusions in annealed samples is changed from 220 to 132, meanwhile the average size and number of inclusions also show a similarly decreasing trend because of Y doping.

Rare earth elements with prominent activity, have affinity a strong affinity with harmful elements (O, S, As, Pb, etc.) that are not conducive to properties of steels, which has been recognized by metallurgical scholars. Besides, RE elements are known as strong sulfide, oxide, or oxysulfide formers, affect some properties of steel, such as impact toughness, corrosion resistance and magnetic properties. Research demonstrates that most of Y particles exist in inclusions, and the reaction equations are described as follows.

\[ 2[\text{Y}] + \text{Al}_2\text{O}_3(S) \rightleftharpoons 2[\text{Al}] + \text{Y}_2\text{O}_3(S) \]  
\[ 2[\text{Y}] + \text{Al}_2\text{O}_3(S) \rightleftharpoons [\text{Al}] + \text{Y}_2\text{AlO}_3(S) \]

According to the free energy of RE inclusions at same condition, the generation possibility of RE inclusions can be determined. The standard formation of free energy of inclusions is calculated as follows.

\[ \Delta G^0 = \Delta H^0 - T\Delta S^0 \]

\[ \Delta G^0 = -1792.600 + 658.0T \]  
\[ \Delta G^0 = -1714.580 + 629.7T \]  
\[ \Delta G^0 = 78.020 - 28.3T \]

\[ \Delta G^0 = \Delta G^0 + RT\ln J \quad T = 1873K \quad J = 0.05146 \]

\[ = 78.020 - 28.3T \]

\[ = -46.201.7 \]

\[ = -21187.6 \quad J / \text{mol} < 0 \]

It is well known that the majority of Al₂O₃ inclusions are generated in deoxidation process of molten steel, while Y₂AlO₃ inclusions are formed in molten steel during smelting when Y element is added to steel. Under the temperature of steel smelting, 1873 K (1600°C), Y₂O₃ inclusions are transformed into Y₂AlO₃ inclusions in Y-doped steel, and Y₂AlO₃ inclusions are more likely to occur after adding Y according to aforesaid relevant chemical reactions.

The through-thickness \( \phi = 45° \) sections of ODF calculated by XRD in annealed sheets are shown in Fig. 8. It is clearly shown in Fig. 8(a), after annealing, the whole intensities of \( \alpha \)-fiber textures in the surface layer are significantly reduced, while more \( \alpha \)-fiber textures occur in \( S = 1.0 \) layer of Y-doped sample A2 (Fig. 8(d)). Some Goss textures appear in \( S = 0.5 \) layer of sample A1 (Fig. 8(b)), while no \( \{110\} < 001 > \) Goss texture occurs in sample A2 because few “Goss seed” exists in warm-rolled Y-doped alloy. In \( S = 0 \) layer, the textures of non-Y-doped sample A1 are mainly composed of stronger \( \gamma \)-fiber textures and relatively scattered \( \alpha \)-fiber textures, and pronounced \( \gamma \)-fiber textures are concentrated on \( \{111\} < 112 > \) component (Fig. 8(c)). By contrast, the textures of sample A2 are dominated by high intensities of \( \alpha \)-fiber textures, as shown in Fig. 8(f).

| Table 2. Inclusion size and number per unit area (1 mm²) in the steels. |
|-----------------|-----------------|-----------------|-----------------|
|                 | A1 rolled sheet | A2 rolled sheet | A1 annealed sheet | A2 annealed sheet |
| Average inclusion size (μm) | 3.9 | 1.4 | 5.6 | 1.7 |
| Inclusion number | 220 | 132 | 324 | 188 |

Fig. 8. Through-thickness \( \phi = 45° \) sections of ODF calculated by XRD in annealed sheets: (a, b, c) sample A1 and (d, e, f) sample A2. (Online version in color.)
For the silicon steels produced by warm rolling, it is generally agreed that the primary Goss grains are inherited from warm rolled sheets, and \{110\} recrystallized grains at the shear bands induce the texture difference. During warm rolling, a large number of Goss texture (\{110\} recrystallized grains) is exhibited in \{111\} in-grain shear bands of sample A1 (Fig. 2(a)) which can serve as “Goss seeds”. However, few “Goss seed” exists in warm-rolled sample A2 sheet (Fig. 2(b)), which leads to the inexistence of Goss texture in \(S = 0.5\) layer after annealing.

The larger \(\text{Al}_2\text{O}_3\) inclusions that have characteristics of the higher mismatch can improve the interface energy between large-sized inclusions and matrix,\(^{19,20}\) thereby increasing the tendency of \(\gamma\)-fiber recrystallization nucleation. While fine \(\text{Y}_2\text{AlO}_3\) inclusions increase the resistance of \(\gamma\)-fiber recrystallization nucleation, hindering the development of \{111\} textures, meanwhile there is a high interfacial energy existing between \{100\} orientation and \(\text{Y}\)-inclusions, thereby creating favorable growth conditions for \{100\} grains. Then \(\lambda\)-fiber textures of \(\text{Y}\)-doped sample A2 are enhanced due to \(\text{Y}\) addition after annealing.

In BCC iron, the \(<001>\) direction is the easiest magnetization direction, then \(\lambda\)-fiber textures with two easy magnetization orientations comprising \{001\}<001>, \{001\}<011> textures have excellent soft magnetic properties.\(^{21–26}\) While \(\gamma\)-fiber textures such as \{111\}<110> and \{111\}<112> textures considered to the worst textures cause a decline in the magnetic properties of silicon steels.\(^{27–32}\)

### 3.3. Effect of Y on Soft Magnetic Properties

Figure 9 presents the hysteresis curves in the measurements of \(B_8\) and \(P_{10/1000}\) of annealed sheets. In the measurements of magnetic inductions, \(B_8\) and remanence (\(B_r\)) of non-Y-doped sample A1 are 1.295 T and 1.158 T (Fig. 9(a)), while \(B_8\) and \(B_r\) values of \(\text{Y}\)-doped sample A2 increase to 1.493 T and 1.206 T (Fig. 9(b)), which may be attributed to the increase of favorable \{100\}<0vw> textures. It is observed that \(P_{10/1000}\) value of sample A2 is lower than that of sample A1 based on the area of hysteresis loop at high frequency magnetic field, as shown in Figs. 9(c)–9(d). It is worth noting that the coercive force (\(H_c\)) is on the decline due to a decrease in the number of inclusions with nonmagnetic characteristic after adding \(\text{Y}\).

It is well known that the iron loss of silicon steels is composed of hysteresis loss (\(P_h\)), eddy current loss (\(P_e\)) and abnormal iron loss (\(P_a\)). According to the theory presented by Bertotti,\(^{33}\) the total iron loss (\(P_t\)) can be expressed by:

\[
P_t = P_h + P_e + P_a = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^\beta \quad \ldots \quad (6)
\]

where \(f\) is the frequency, \(B\) is the magnetic flux density, and \(k_h, k_e, k_a, \alpha,\) and \(\beta\) are assumed to be constants. When \(B=1.0\) T

\[
P_t = P_h + P_e + P_a = k_h f + k_e f^2 + k_a f^{1.5} \quad \ldots \quad (7)
\]

The coefficient of \(k_h\) can be calculated by fitting the values of \(P_{10/50}, P_{10/400},\) and \(P_{10/1000}\) to Eq. (7), and they are measured at 50 Hz, 400 Hz and 1 000 Hz, respectively. The

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Fig. 9. Hysteresis curves in the measurements of \(B_8\) and \(P_{10/1000}\) of annealed sheets: (a) DC-hysteresis curves of sample A1; (b) DC-hysteresis curves of sample A2; (c) AC-hysteresis curves at 1 000 Hz of sample A1 and (d) AC-hysteresis curves at 1 000 Hz of sample A2. (Online version in color.)
average magnetic inductions and iron losses are presented in Table 3. $k_b$, $k_e$, and $k_d$ for sample A1 obtained by Eq. (7) are $7.519 \times 10^{-3}$, $2.475 \times 10^{-6}$ and $2.9 \times 10^{-4}$. In the case of 1 000 Hz, $P_h$, $P_r$, $P_a$, and $P_d$ for sample A1 are 7.519 W/kg, 2.475 W/kg and 9.171 W/kg. For sample A2, $k_b$, $k_e$, and $k_d$ are $6.346 \times 10^{-3}$, $2.45 \times 10^{-6}$ and $2.7 \times 10^{-4}$, as well as $P_h$, $P_r$, $P_a$, and $P_d$ obtained at 1 000 Hz are 6.346 W/kg, 2.444 W/kg and 8.538 W/kg, respectively.

Grain boundaries are crystal defects and pin the domain wall movement. Then, the finer grain size can deteriorate $P_h$. Although the decrease of grain size can deteriorate $P_h$, it is favorable to the decrease of total eddy-current loss ($P_e$ + $P_r$). The usage frequency is mainly concentrated in 1 000 Hz high-frequency motor, where the ratio of $P_h$ + $P_r$ is higher than 60%, while $P_h$ only accounts for about 40%. In this study, the decrease of grain size may reduce the values of $P_h$, thus Y-doped sample with smaller grains exhibits lower iron loss $P_{10/1000}$.

### 4. Conclusions

The role of inclusion, microstructure and texture evolution in soft magnetic properties of Fe–6.9 wt%Si alloy with yttrium doping was investigated, and the main conclusions were summarized as following:

1. Adding rare earth Y can suppress the nucleation of {110} orientation grains at {111} in-grain shear bands during warm rolling, and refine the grain size after annealing, meanwhile the average size and number of inclusions also show a similarly decreasing trend because of Y doping.
2. The maximum interface energy between fine Y-inclusions and {100} grains possibly induces the grain growth of {100} grains, meanwhile {111} <112> and {111} <110> textures are transformed into {100} <uvw> textures after adding rare earth Y.
3. $B_s$ and $B_o$ of non-Y-doped alloy measured at 800 A/m are 1.295 T and 1.158 T, and they increase to 1.493 T and 1.206 T due to Y doping, which can be attributed to the increase of favorable {100} <uvw> textures.
4. Based on the area of hysteresis loop at high frequency magnetic field, $P_{10/1000}$ value of Y-doped alloy is lower than that of non-Y-doped alloy because of the increase of favorable {100} <uvw> textures and the decrease of grain size.

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### REFERENCES


### Table 3. Measurement results of magnetic properties of annealed sheets.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Magnetic induction</th>
<th>Iron loss (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B_s$ (T)</td>
<td>$B_o$ (T)</td>
</tr>
<tr>
<td>A1</td>
<td>1.295</td>
<td>1.158</td>
</tr>
<tr>
<td>A2</td>
<td>1.493</td>
<td>1.206</td>
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