1. Introduction

Non-oriented electrical steels is one of the most important industrial soft magnetic materials, which are widely used in electrical appliances and devices as the core materials, for example, motors, generators, ballast and transformers. Magnetic induction and iron loss are the main magnetic properties of non-oriented electrical steels. The former as an important parameter for evaluating magnetic properties is closely connected with crystallographic texture. It is well known that among the textures of iron silicon alloys, the \(<100>\) axes are magnetized easiest, \(<111>\) are the most difficulty and \(<110>\) are medium. So, more component of favorable textures \{100\}<uvw> and \{110\}<uvw> should be obtained while \{111\}<uvw> texture should be reduced in the microstructure of non-oriented electrical steels for improving magnetic properties.\(^1\) Much works on optimizing texture of non-oriented electrical steels by production technology have been done, for instance, increasing heating rate of recrystallization annealing\(^2,3\) and optimizing the processing of hot rolling, cold rolling and coiling.\(^4,7\) However, few attempts have been made, at present, to investigate the effect of compositions on texture of non-oriented electrical steels. Although, some researches for ameliorating texture by adding rare earth elements have been carried out\(^8,9,10\) the mechanism is still lacking understanding. The aim of this present work is to elucidate the mechanism of Ce on the improving magnetic property of non-oriented electrical steel by systematically investigating effect of Ce on the recrystallization texture of a 1.2%Si-0.4%Al non-oriented electrical steel.

2. Experimental

The chemical composition of two non-oriented electrical steels with different Ce content is listed in Table 1. According to authors’ previous work,\(^11\) it is best beneficial for the magnetic properties of non-oriented electrical steel to addition 0.0051% Ce. So, for convenient research, the 0% and 0.0051 wt% Ce content were choose in this paper. The steels were prepared in a 15 Kg vacuum induction furnace and cast into 50 mm \(\times\) 100 mm \(\times\) 400 mm ingots. The steel ingots were reheated to 1 160 °C for 40 min, and hot rolled to 2.5 mm thickness plates by a reversing hot rolling mill. The finishing hot-rolled and coiling temperature were conducted at 870 °C and 680 °C. The hot-rolled plates were annealed at 1 000 °C for 5 min followed by air cooling, and then were cold rolled to 0.5 mm by 78% reduction using a laboratory mill through 6 passes. Subsequently, the cold-rolled plates were annealed at 600–700 °C at intervals of 25°C for 5 min in the 100% Ar atmosphere and followed by

<table>
<thead>
<tr>
<th>specimen</th>
<th>Si</th>
<th>Al</th>
<th>Mn</th>
<th>C</th>
<th>S</th>
<th>O</th>
<th>Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.16</td>
<td>0.42</td>
<td>0.35</td>
<td>0.0038</td>
<td>0.0019</td>
<td>0.0035</td>
<td>0</td>
</tr>
<tr>
<td>#2</td>
<td>1.20</td>
<td>0.46</td>
<td>0.32</td>
<td>0.0026</td>
<td>0.0027</td>
<td>0.0034</td>
<td>0.0051</td>
</tr>
</tbody>
</table>
water quenching in order to obtain different recrystallized fraction (microstructure).

Before texture measurements, the specimens were mechanically polished first and then electropolished in a solution of 400 ml alcohol and 100 ml HClO₄ for removing the deformation layer introduced during previous mechanical polishing. The texture examinations of specimens in surface were carried out in CHANNL5 electron backscatter diffraction (EBSD) system attached with ZEISS SUPRA 55 scanning electron microscope (SEM). The orientation distribution function (ODF) was analyzed by a texture analysis software (TSL OIM Analysis 6). The step size used during measurement is 1 μm per step for recrystallization stage.

3. Results and Discussion
3.1. Microstructure Evolution during Recrystallization

The microstructure evolution during recrystallization

![Fig. 1. Optical microstructures of recrystallized specimens with 0% and 0.0051% Ce annealed at different temperature (a) 600°C, (b) 625°C, (c) 650°C, (d) 675°C, (e) 700°C.](image)
and the recrystallized fraction as a function of annealing temperature in specimens with 0% and 0.0051% Ce are shown in Figs. 1 and 2 respectively. It is found that recrystallized fraction of specimens with 0% and 0.0051% Ce content increases with the annealing temperature. However, the recrystallized fraction of specimens with 0.0051% Ce content is higher than that of specimens without Ce element. It means that recrystallization occurred in specimens with Ce is faster than that in ones without Ce at the same annealing temperature. As known to all, the process of recrystallization is mainly affected by the purity of metal, cold deformation rate, initial grain size, etc. The driving force of recrystallization is the stored energy due to deformation. The higher stored energy occurs in specimens, the faster kinetics of recrystallization is achieved. Moreover, the purity of metal is higher, the recrystallization temperature is lower. The addition of Ce rare earth in non-oriented electrical steels not only purified the metal for reducing inclusions, for example MnS, in steel but also may enhance the driving force of recrystallization due to the solid solution of Ce. This is mainly because solid solution of Ce can induce lattice distortion of alloys that improved the deformation stored force. While, according to Fang’s work, some Ce will be solid solute in non-oriented steel under the experimental condition of this paper (S: 0.0027%, O: 0.0034%). All of these above could improve recrystallization, thus, the nucleation of recrystallization occurred in specimens with Ce is very easier than that in specimens without Ce, as shown in Figs. 1, 2.

3.2. Texture Evolution during Nucleation of Recrystallization

Figures 3 and 4 display the inverse pole figure map and \( \phi_2 = 45^\circ \) sections of the ODF for specimens with 0% and 0.0051% Ce content during the initial stage of recrystallization respectively (annealing at 600°C). It can be seen that the recrystallization fraction of specimens with 0.0051% Ce content is higher than that of specimens without Ce, although they are all lower level (see Fig. 3). The typical texture in specimens is consisted of strong \( \gamma \)-fiber, weak Cube and Goss components, their intensity are 3.2, 2.4 and 2.4 (see Fig. 4). However, the texture in specimens is consisted of very strong Cube and weak \( \gamma \)-fiber components, their intensity are 5.7 and 2.7. The effect of Ce on the orientation intensity of \( \alpha \)-fiber and \( \gamma \)-fiber texture in the initial recrystallization stage is shown in Fig. 5. It indicates the orientation intensity of \{112\}<110>, \{111\}<110> and \{111\}<112>, \{111\}<112> texture in specimens without Ce element is higher than that of specimens with 0.0051% Ce content.

On the base of above results, the recrystallization texture components are closely affected by Ce element at the initial stage of recrystallization (nucleation). It is attributed to, on the one hand, the purifying of moderate Ce rare earth in steel. Figure 6 displays the distribution of inclusions in specimens with 0% and 0.0051% Ce content and the statistical data of inclusions. One can see that there is few fine inclusions in specimens with 0.0051% Ce content, and because \{111\} oriented grains nucleate and grow at inclusions preferentially. So, the orientation intensity of \{111\} texture in specimens with 0.0051% Ce is lower than that of specimens without Ce. On the other hand, some Ce may be segregated at grain boundaries and degrade the grain-boundary energy. Thus, the nucleation and growth of

Fig. 2. Evolution of recrystallized fraction as a function of annealing temperature in different specimens with and without Ce.

Fig. 3. Orientation map at the very early stage of recrystallization in specimens with (a) 0%, (b) 0.0051% Ce content and (c) inverse pole figure.

Fig. 4. \( \phi_2 = 45^\circ \) sections of the ODF for recrystallized grains at the initial stage of recrystallization in specimens with (a) 0% and (b) 0.0051% Ce content.
{111} texture component at grain boundaries preferentially may be impeded and the intensity is weak.

3.3. Texture Evolution during Recrystallization

After nucleation of recrystallized grains finished, recrystallization is proceeding with annealing temperature from 625 to 700°C. Figure 7 shows the φ2 = 45° sections of the ODF for recrystallized grains in specimens with 0% and 0.0051% Ce content annealed at 625–700°C. The main textures in specimens without Ce annealed at 625°C are {112} < 131 > and {111} < 112 > components, their intensity are 2.8 and 2.5 respectively. Some weak Goss texture components also exist in specimens without Ce (Fig. 7(a)). However, Cube texture and strong Goss texture components are the main textures in specimens with 0.0051% Ce content, and the intensity of fiber is weak. The intensity of Cube and Goss components are 2.8 and 2.7 respectively. Although there are the same texture type in all specimens annealed at 650°C, including Cube, Goss and {112} < 131 > textures, their intensity are different for specimens with and without Ce element. The intensity of Cube texture in specimens with Ce is stronger than that in ones without Ce. Nevertheless, the intensity of Goss and {112} < 131 > textures components in specimens with Ce element is weaker than that in specimens without Ce. The textures in specimens with and without Ce annealed at 675°C and 700°C are consisted of Cube, Goss and γ-fiber textures. The intensity of Cube and Goss textures in specimens with Ce is stronger than that in specimens without Ce, but the intensity of γ-fiber texture in specimens with Ce is weaker. And some stronger α-fiber texture appears in specimens annealed at 700°C without Ce.

The area fraction of each texture component in 1.2%Si-0.4%Al specimens with and without Ce annealed at different temperature is indicated in Fig. 8. It can be seen that with annealing temperature the area fraction of {110} component texture in specimens without Ce increases markedly, {111} component texture intensity degrades observably and {100} component doesn’t change in the mass except in specimens annealed at 625°C, seen in Fig. 8(a). In specimens with 0.0051% Ce content, the area fraction of {100} component texture in specimens without Ce increases significantly, {111} component decreases and {110} component doesn’t change in the mass, as shown...
The area fraction of \{100\} component texture in specimens with Ce is more than that in ones without Ce. The \{100\}/\{111\} and \{(100)+(110)\}/\{111\} texture factors of nucleation during recrystallization of specimens without Ce and with 0.0051% Ce annealed at different temperature is shown in Fig. 9. One can see that the two texture factors values increase with increasing of annealing temperature. And the values of specimens with 0.0051% Ce are higher than that of specimens without Ce. So, the favourable \{100\} and \{110\} textures fraction in specimens with Ce are more than that in ones without Ce. This is attributed to the effect of Ce on the texture type in non-oriented electrical steel.

The final type of recrystallization texture in steel is mainly decided by the nucleus orientation during nucleation of recrystallization.\(^{17}\) According to the reports in the literature, the \{111\} orientation recrystallized grains nucleate and grow preferentially nearly the fine inclusions.\(^{14}\) Apparently, inclusions play an important role of influence textures in specimens. The formation of Ce-oxides, Ce-sulphides and Ce-sulfur oxides cannot only inhibit MnS inclusion precipitation in specimens with 0.0051% Ce content, but also coarsen and modify Al\(_2\)O\(_3\) inclusion morphology and spheronize AlN inclusion as its precipitation nucleus, as shown in Fig. 10. It can be seen that the main inclusions in specimens without Ce are the fine MnS, AlN and irregular Al\(_2\)O\(_3\). While, in specimens with 0.0051% Ce the complex spherical and coarse Ce-oxides, Ce-sulphides and Ce-sulfur oxides inclusions are formed. So, addition of 0.0051% Ce in non-oriented electrical steel can reduce drastically the inhabitation effect of grain boundaries movement due to the previous inclusions precipitation and also restrain the nucleation and growth of \{111\} orientation grains.

Fig. 7. \(\phi^2 = 45^\circ\) sections of the ODF for recrystallized grains in specimens with 0% and 0.0051% Ce content annealed at different temperature (a) 625\(^\circ\)C, (b) 650\(^\circ\)C, (c) 675\(^\circ\)C, (d) 700\(^\circ\)C.

Fig. 8. Ratio of the specific orientation in the total recrystallized grains (a) 0% Ce (b) 0.0051% Ce.

Fig. 9. The variation in texture factors of (100)/(111) (a) and (100)+(110)/(111) (b) in specimens with 0% and 0.0051% Ce content during nucleation of recrystallization with annealing temperature.
4. Conclusions

(1) The recrystallized fraction of specimens with 0% and 0.0051% Ce content increases with the annealing temperature. However, the recrystallization kinetics in specimens with Ce is faster than in ones without Ce. The recrystallized fraction of specimens with 0.0051% Ce content is higher than that of specimens without Ce.

(2) The effect of Ce on the evolution of recrystallization texture in non-oriented electrical steel is very important and significant. Recrystallized grains in specimens containing Ce are coarser than that in specimens without Ce and the intensity of favorable {100} and {110} textures are also stronger. Meanwhile, the intensity of γ-fiber texture component is weak in specimens containing Ce.

(3) The presence of Ce-oxides, Ce-sulphides and Ce-sulfur oxides in specimens with 0.0051% Ce not only inhibited MnS inclusion precipitation, but also coarsened and modified Al₂O₃ inclusion morphology and spherified AlN inclusion. These result in unfavorable textures component decreased and favorable ones increased in specimens containing Ce.

REFERENCES