

VIEWPOINT

Influence mechanism of rare earth (RE) on inclusion modification in non-oriented silicon steel

Haijun Wang^{1,2} , Kaixuan Shao^{1,2} , Yuhao Niu^{1,2,3} , Jialong Qiao^{1,2,3,4,*}, Hongbo Pan^{1,2,**},
and Shengtao Qiu^{1,3}

¹ Anhui Province Key Laboratory of Metallurgical Engineering & Resources Recycling, Anhui University of Technology, Maanshan 243002, China

² School of Metallurgical Engineering, Anhui University of Technology, Ma'anshan, Anhui, Maanshan 243032, China

³ Iron and Steel Research Institute Co., Ltd., Beijing 100081, China

⁴ Silicon Steel & Sheet Business Division, Xinyu Iron and Steel Group Co., Ltd., Xinyu 338001, China

Received: 26 July 2024 / Accepted: 24 September 2024

Abstract. Effects of rare earth (La+Ce) on inclusions in hot-rolled band of 3.0~3.3%Si-0.8~1.0%Al non-oriented silicon steel was studied using industrial trials, scanning electron microscope (SEM) and thermodynamic analysis. Furthermore, combining Heterogeneous Nucleation Theory with Edge-to-Edge Matching (E2EM) model, the formation mechanism of complex inclusions was also investigated. Rare earth (La+Ce) would promote the spheroidization and coarsening of inclusions, and then transform into regular and near circle morphology composite inclusions of rare earth. The low content of rare earth (21 ppm) mainly deoxidized and modified Al_2O_3 inclusions, and formed $(\text{La,Ce})\text{AlO}_3$ inclusions. Increasing of rare earth (29–45 ppm) would promote the formation of $(\text{La,Ce})\text{AlO}_3$ – $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$ inclusions, reduce the sulfide precipitation, and promote a gradual transformation of the core of composite inclusions from $(\text{La,Ce})\text{AlO}_3$ to $(\text{La,Ce})\text{AlO}_3$ – $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$, which agreed well with the thermodynamic analysis. However, rare earth (29–45 ppm) had a weak metamorphic effect on Al_2O_3 inclusions generated by temperature drop and secondary oxidation. LaAlO_3 , CeAlO_3 , $\text{La}_2\text{O}_2\text{S}$ and $\text{Ce}_2\text{O}_2\text{S}$ could be the heterogeneous nucleation core of AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$, typical composite inclusions with $(\text{La,Ce})\text{AlO}_3$ and $(\text{La,Ce})_2\text{O}_2\text{S}$ as the core would ultimately form.

Keywords: non-oriented silicon steel / rare earth(La+Ce) / inclusion / heterogeneous nucleation theory / edge-to-edge matching model

1 Introduction

Non-oriented silicon steel is an important iron-based soft magnetic material, which is mainly used in the cores of drive motors for hybrid and electric vehicles [1–5]. Low core loss and high magnetic induction are the most significant requirements for non-oriented silicon steel, which would be severely deteriorated by inclusions [6–11].

Since rare earth elements have a high affinity with oxygen and sulfur, and widely used to modify inclusions and promote properties of steel products [12–15]. Additionally, rare earth inclusions could form composite inclusions with Al_2O_3 , MnS , AlN , etc., and promote their spheroidization, thereby reducing the adverse impact on the magnetic properties of non-oriented silicon steel [12,16].

Rare earths used in non-oriented silicon steel are mainly lanthanum, cerium and heavy rare earth yttrium, generally in the form of a variety of rare earth alloys added to the liquid steel. Because of lanthanum, cerium, the total amount of more, the study and use of its more extensive, contribute to cost reductions and efficiency gains. Many scholars have also studied the effect of lanthanum and cerium on the evolution of inclusions [17,18]. Currently, extensive research has been conducted on characterizing and thermodynamically calculating the modification mechanism of rare earth on inclusions which mainly derived from laboratory experiments conducted with high levels of rare earth content [19–27]. However, in addition to the beneficial effects of rare earth in non-oriented silicon steels [28,29], rare earth would also lead to an increase in the cost of steel and elevate the risk of water nozzle blockage [30].

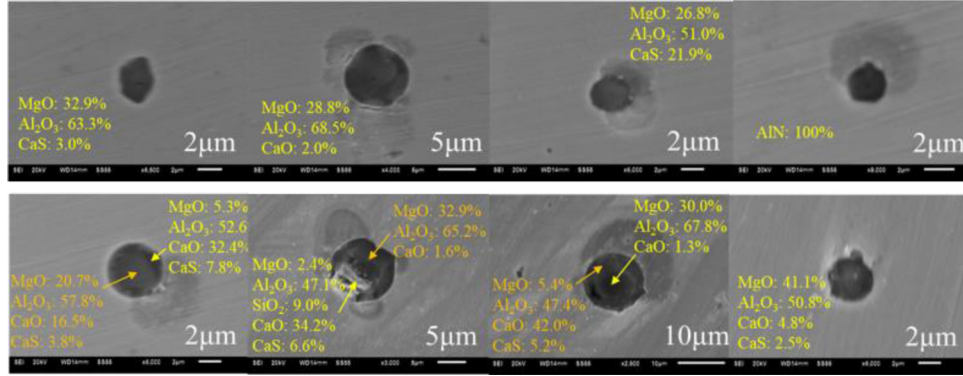
As a consequence, conducting industrial trials is crucial to validate and optimize the content of rare earth addition for practical applications in non-oriented silicon steel

* e-mail: qiaojialong2015@126.com

** e-mail: 20130007@ahut.edu.cn

Table 1. The chemical composition of non-oriented silicon steels (wt, %).

Samples	C	Mn	S	P	Si	Als	N	La+Ce
Re-0	0.0024	0.27–0.29	0.002	0.012	3–3.3	0.8–1	0.0020	0
Re-21	0.0024	0.27–0.29	0.002	0.013	3–3.3	0.8–1	0.0021	0.0021
Re-29	0.0024	0.27–0.29	0.002	0.015	3–3.3	0.8–1	0.0020	0.0029
Re-45	0.0021	0.27–0.29	0.002	0.012	3–3.3	0.8–1	0.0020	0.0045

**Fig. 1.** Typical inclusions in the Hot-rolled bands of Re-0.

production. Effects of Rare Earth(La+Ce) on inclusions in 3.0–3.3%Si-0.8–1.0%Al non-oriented silicon steel were systematically studied using industrial trials, thermodynamic analysis, and Scanning Electron Microscope(SEM). Furthermore, combining Heterogeneous Nucleation Theory with Edge-to-Edge Matching (E2EM) model, the formation mechanism of composite inclusions was also investigated, which is another main focus of the current paper.

2 Materials and methods

The chemical composition of non-oriented silicon steels used in the present study is given in Table 1 (in the subsequent research process, the test steels were named Re-0, Re-21, Re-29 and Re-45). Re-0 followed the conventional process without the addition of rare earth, while Re-21, Re-29 and Re-45 incorporated varying amounts of lanthanum-cerium alloy during the RH refining process. Apart from the varying rare earth content in the molten steels, the process routes for the four non-oriented silicon steels remained consistent. The alloying elements, aluminum, and silicon contents were relatively similar among the four samples. Furthermore, La+Ce content in Table 1 was determined through ICP-MS analysis.

Hot-rolled bands of 3.0–3.3%Si-0.8–1.0%Al non-oriented silicon steel were directly sampled after the hot rolling process, and a wire-cutting technique was employed to prepare samples with dimensions of 8mm (TD) × 10mm (RD). The hot-rolled bands through grinding and polishing were prepared into SEM samples, magnifying in a corresponding multiple and observing with 100 fields of view under SEM. The types and sizes of non-metallic inclusions in the hot-rolled bands were counted, using Oxford X-Max50, linked with FEI Quanta 650FEG SEM and IPP (Image-Pro Plus) software.

3 Results and discussions

3.1 Characteristics of typical inclusions

Figure 1 shows the morphological types of typical inclusions in the hot-rolled bands of Re-0. Inclusions in hot-rolled bands of Re-0 sample primarily are composite inclusions, which consist of oxides (MgO, Al₂O₃, CaO, etc.) and sulfides (CaS), along with a portion of AlN. Among them, the composite inclusions predominantly exhibit spherical or near-spherical shapes, such as MgO-Al₂O₃-CaO-CaS and MgO-Al₂O₃-CaO, whereas the AlN inclusions exhibit an irregular square shape. The outer layers of some composite inclusions contain small amounts of SiO₂ inclusions due to the silicon alloying process present in the molten steel before the aluminum deoxidation process reaches equilibrium, where partial oxidation changes to inclusions and is left behind.

Figure 2 illustrates the morphological types and compositional scanning results of typical inclusions in the hot-rolled bands of Re-21, Re-29, and Re-45 samples. The types of inclusions are mainly composite inclusions. The main composite inclusion types in hot-rolled bands of Re-21 non-oriented silicon steel are (La,Ce)AlO₃-(MgO-Al₂O₃-CaO), (La,Ce)AlO₃-AlN, and (La,Ce)AlO₃-CaS, along with a portion of (La,Ce)AlO₃-(La,Ce)O₂S-AlN. All of the composite inclusions consist of a (La,Ce)AlO₃ core, while the outer layer comprises the other conventional inclusions. However, the main type of inclusions in Re-29 and Re-45 samples are (La,Ce)AlO₃-(La,Ce)₂O₂S-AlN and (La,Ce)₂O₂S-AlN, respectively. Moreover, small amounts of Calcium are inevitably brought in during the smelting and refining of steel and react to form CaS attached to the exterior of the main inclusions. The morphology of typical inclusions in Re-29 and Re-45 samples is the same as Re-21

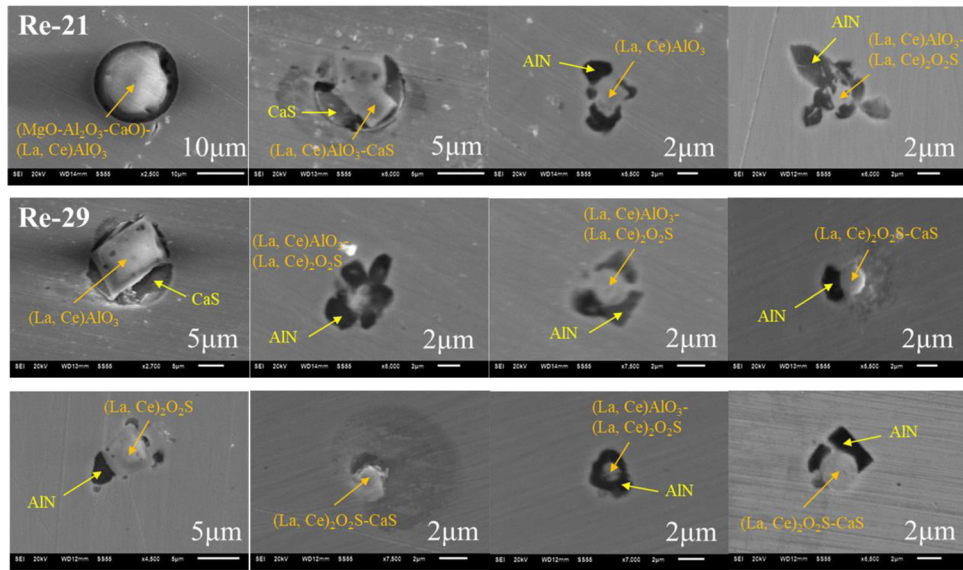


Fig. 2. Typical inclusions in the Hot-rolled bands of Re-21, Re-29 and Re-45 samples.

non-oriented silicon steel. Nonetheless, the core of composite inclusions in Re-29 and Re-45 are $(\text{La,Ce})\text{AlO}_3$ - $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$, respectively. Based on the comprehensive analysis of the aforementioned detection results, it could be concluded that an increase in rare earth content leads to a gradual transition of the primary type of rare earth inclusion from $(\text{La,Ce})\text{AlO}_3$ to $(\text{La,Ce})_2\text{O}_2\text{S}$.

To summarize, rare earth (La+Ce) would obviously promote the spheroidization and coarsening of inclusions. Inclusions in hot-rolled bands of 3.0–3.3%Si-0.8–1.0%Al non-oriented silicon steel with low rare earth content changed obviously, and types of inclusions are mainly $(\text{La,Ce})\text{Al}_2\text{O}_3$ +conventional inclusions, which consist of a $(\text{La,Ce})\text{AlO}_3$ core. With increasing rare earth content, inclusions are mainly $(\text{La,Ce})_2\text{O}_2\text{S}$ +conventional inclusions, core of composite inclusions changed from $(\text{La,Ce})\text{AlO}_3$ to $(\text{La,Ce})\text{AlO}_3$ - $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$.

3.2 Modification and distribution of inclusions

Inclusions in non-oriented silicon steel have significant impacts on magnetic properties and mechanical properties [31–35]. As rare earth alloys (La+Ce) were invested into the RH refining furnace, La and Ce would exhibit a strong affinity towards the elements [O] and [S] and transform oxide and sulfide inclusions into rare earth inclusions. At relatively low levels of rare earth content (21 ppm), the predominant rare earth inclusions consist of $(\text{La,Ce})\text{AlO}_3$. As increasing rare earth (29–45 ppm), the primary types of rare earth composite inclusions are $(\text{La,Ce})\text{AlO}_3$ - $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$.

Summing up, the detection results of inclusions provide clear evidence for the transition sequence of stable rare earth inclusions as the rare earth content in the steel increases from 0 to 45 ppm, and the variation of the inclusion composition was $\text{Al}_2\text{O}_3 \rightarrow (\text{La,Ce})\text{AlO}_3 \rightarrow (\text{La,Ce})\text{AlO}_3$ - $(\text{La,Ce})_2\text{O}_2\text{S} \rightarrow (\text{La,Ce})_2\text{O}_2\text{S}$.

Meanwhile, combined with the previous research results of the research group [36] and detection results, La+Ce in non-oriented silicon steel would promote the spheroidization and coarsening of inclusions [37]. With the increase of rare earth content in non-oriented silicon steel, the changing trend of inclusion morphology was “Irregular morphology (e.g., conventional inclusions)→Regular angular morphology (e.g., $(\text{La,Ce})\text{AlO}_3$)→Regular angular morphology+ Near circle morphology (e.g., $(\text{La,Ce})\text{AlO}_3$ + $(\text{La,Ce})_2\text{O}_2\text{S}$)→Near circle+non-angular morphology (e.g., $(\text{La,Ce})_2\text{O}_2\text{S}$)→Near circle morphology (e.g., $(\text{La,Ce})_x\text{S}_y$)” (as shown in Fig. 3).

The distribution of microscopic inclusions (1–5 μm) and fine inclusions (0.2–1 μm) in hot-rolled bands of 3.2%Si-0.9%Al non-oriented silicon steel with different rare earth contents was studied by SEM and IPP. The distribution results are shown in Figure 4.

The distribution results of micro-inclusions (1–5 μm) and fine-inclusions (0.2–1 μm) in hot-rolled bands in Figure 4 show that with changing of rare earth content in non-oriented silicon steel, distribution of inclusions changed obviously, and distribution density of inclusions in Re-45 increased markedly. The distribution density of inclusions in Re-21 and Re-29 decreases obviously, and the average size of fine-inclusions increases obviously, which will affect the grain growth during annealing, and then affect the magnetization process and magnetic properties of non-oriented silicon steel.

In order to systematically analyze the modification mechanism of rare earth inclusions in non-oriented silicon steel in detail, the morphology, composition and size of 0.2–5 μm inclusions of rare earth, Alumina and Sulfide inclusions were statistically analyzed using an Automatic Scanning Electron Microscope (SEM) equipped with an energy dispersive spectrometer (EDS) with an accelerating voltage of 15 kV as shown in Figure 5. Within the scanning area of 20 mm^2 , the number of rare earth inclusions increased sharply, and the average size increased gradually

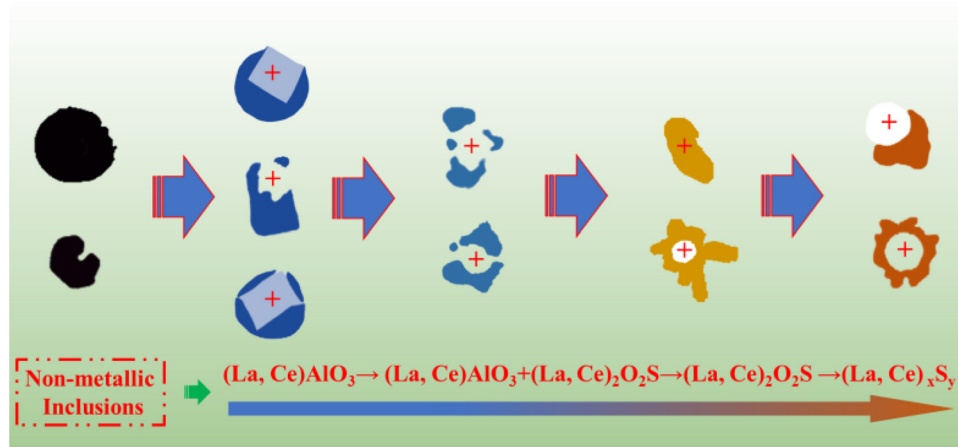


Fig. 3. Schematic diagram of inclusion morphology change.

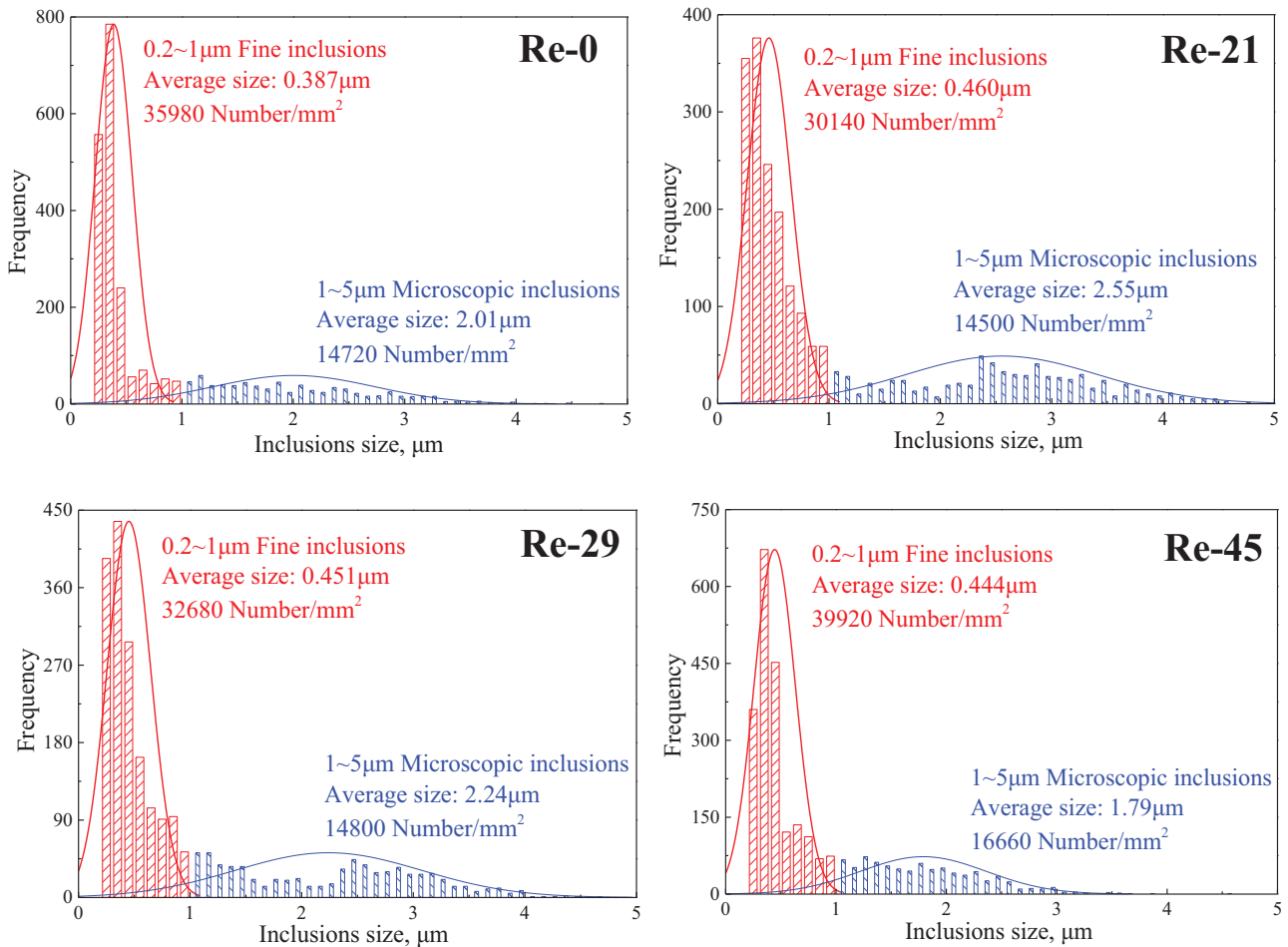


Fig. 4. Distribution of Inclusions in Hot-Rolled bands.

with increasing rare earth content in non-oriented silicon steel. The size and quantity of Sulfu showed a downward trend. The number of Alumina inclusions in Re-21 and Re-29 decreased obviously, and the average size increased. However, the Alumina-type inclusions in Re-45 increased obviously, and the average size changed little compared with that in Re-29.

Therefore, rare earth in non-oriented silicon steel mainly plays the role of deep deoxidation, deep desulfurization and metamorphic inclusions. The morphology and type distribution of micro-inclusions changed obviously after adding rare earth to non-oriented silicon steel, and the types of inclusions were also different with increasing rare earth content. Low content of rare earth (21 ppm) in

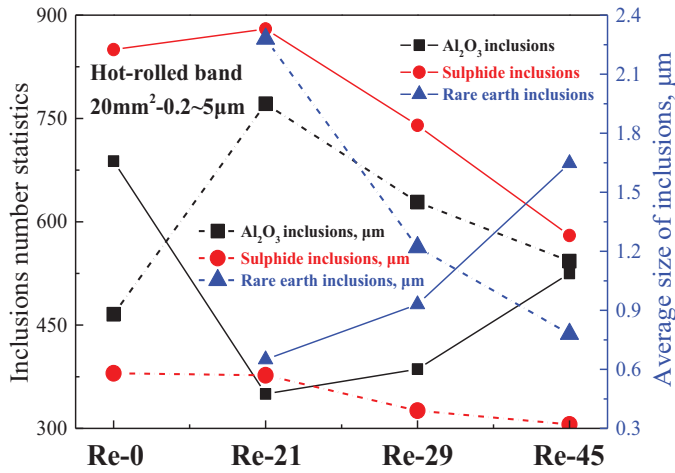


Fig. 5. Distribution statistics of main inclusions in hot-rolled bands.

non-oriented silicon steel mainly deoxidized and modified Al_2O_3 inclusions, and formed $(\text{La,Ce})\text{AlO}_3$ inclusions. Increasing of rare earth content (29–45 ppm) promoted the formation of $(\text{La,Ce})\text{AlO}_3$ – $(\text{La,Ce})_2\text{O}_2\text{S}$ and $(\text{La,Ce})_2\text{O}_2\text{S}$ inclusions and reduced the Sulfide precipitation. However, rare earth (29–45 ppm) had a weak metamorphic effect on Al_2O_3 inclusions generated by temperature drop and secondary oxidation. Eventually, Al_2O_3 inclusions with high rare earth content would increase obviously. Because of the high content, small size, and rolling crushing of Al_2O_3 inclusions, Al_2O_3 inclusions would directly affect the grain growth during annealing, and then affect the magnetization process and magnetic properties of non-oriented silicon steel.

3.3 Thermodynamic of inclusion formation

The $[\text{Ce}]$ – $[\text{S}]$ equilibrium diagrams of non-oriented silicon steel in Table 1 were calculated using C++ programming [36] as shown in Figure 6 (Given the similarities in the physical and chemical properties of La and Ce are similar in steel, the reaction processes of La+Ce in non-oriented silicon steel were analyzed by taking Ce as an example.). $[\text{Ce}]$ content corresponding to the transition of rare earth inclusions during the temperature drop process is shown in Table 2 ($[\text{S}]=20$ ppm).

As shown in Figure 6 and Table 2, with increasing Ce content in non-oriented silicon steel, the transformation order of inclusion containing Ce was $\text{Al}_2\text{O}_3 \rightarrow \text{CeAlO}_3 \rightarrow \text{Ce}_2\text{O}_2\text{S} \rightarrow \text{Ce}_x\text{S}_y$. Under the composition system of 3.0–3.3%Si–0.8–1.0%Al non-oriented silicon steel, a reduction in temperature facilitated the formation of $\text{Ce}_2\text{O}_2\text{S}$ and CeS_x , yet the primary inclusions remained CeAlO_3 and $\text{Ce}_2\text{O}_2\text{S}$.

ΔG of main reactions (as shown in Tab. 3 [36]) in non-oriented silicon steel (Tab. 1) is shown in Figure 7. Under the conditions of RH refining and liquidus temperature (about 1500–1580 °C), reaction (3) and (1) cannot be performed, Reactions (2), (6) and (7) would mainly occur in non-oriented silicon steel. With the continuous decrease of

temperature, reactions, (4), (5), and (8) would be promoted. In the solidification process, decreasing of temperature would promote the reactions of CeS_x and $\text{Ce}_2\text{O}_2\text{S}$.

Therefore, based on results of detections (Fig. 2) and calculations (Figs. 7 and 8), the variation of the inclusions was $\text{Al}_2\text{O}_3 \rightarrow \text{REAlO}_3 \rightarrow \text{RE}_2\text{O}_2\text{S}$ with increasing of rare earth (21–45 ppm), which agreed well with the thermodynamic analysis. Decreasing of temperature promoted the formation of $\text{RE}_2\text{O}_2\text{S}$, but the main inclusions were still REAlO_3 . Moreover, schematic diagram of rare earth inclusions formation of non-oriented silicon steel during RH refining to solidification is shown in Figure 9.

3.4 Formation mechanism of composite inclusions

The addition of rare earth (La+Ce) alloy during the RH refining process of non-oriented silicon steel resulted in the formation of a significant number of composite inclusions comprising $(\text{La,Ce})\text{AlO}_3$ and $(\text{La,Ce})_2\text{O}_2\text{S}$ as the core (as illustrated in Fig. 2). In accordance with the principles of heterogeneous nucleation theory, the melting points of rare earth compounds are all higher than 1690 °C, which meets the basic conditions of the heterogeneous nucleation core of conventional inclusions [37]. The Edge-to-Edge Matching (E2EM) model represents an advanced crystallographic model that extends the two-dimensional misfit model [38], predicts the orientation relationship between crystal structures and has been validated for practical applications. Therefore, Edge-to-Edge Matching (E2EM) model was employed to assess the degree of matching between rare earth inclusions and other inclusions. The calculation formula for the E2EM model is as follows [39].

$$f_r = \frac{|r_M - r_P|}{r_P} \quad (1)$$

$$f_d = \frac{|d_M - d_P|}{d_P} \quad (2)$$

where f_r represents the lattice mismatch in atomic spacing, while f_d represents the lattice mismatch in interplanar spacing. r_M and r_P are the interatomic spacings along the matching directions in the matrix phase and the precipitate, respectively. The parameters d_M and d_P are the interplanar spacings of the matching planes in the matrix phase and the precipitate, respectively.

The crystallographic data necessary for E2EM model calculations was acquired through consultation of the Inorganic Crystal Structure Database (ICSD) and literature. The crystallographic data of rare earth inclusions and typical inclusions in non-oriented silicon steel are shown in Table 4 [40–44]. It is worth noting that previous studies have confirmed a relatively small impact of lattice constant variation caused by thermal expansion on crystallographic calculations [45,46]. Therefore, during the calculation process of the E2EM model, the lattice constants of each phase at room temperature were employed, disregarding the influence of thermal expansion on these constants.

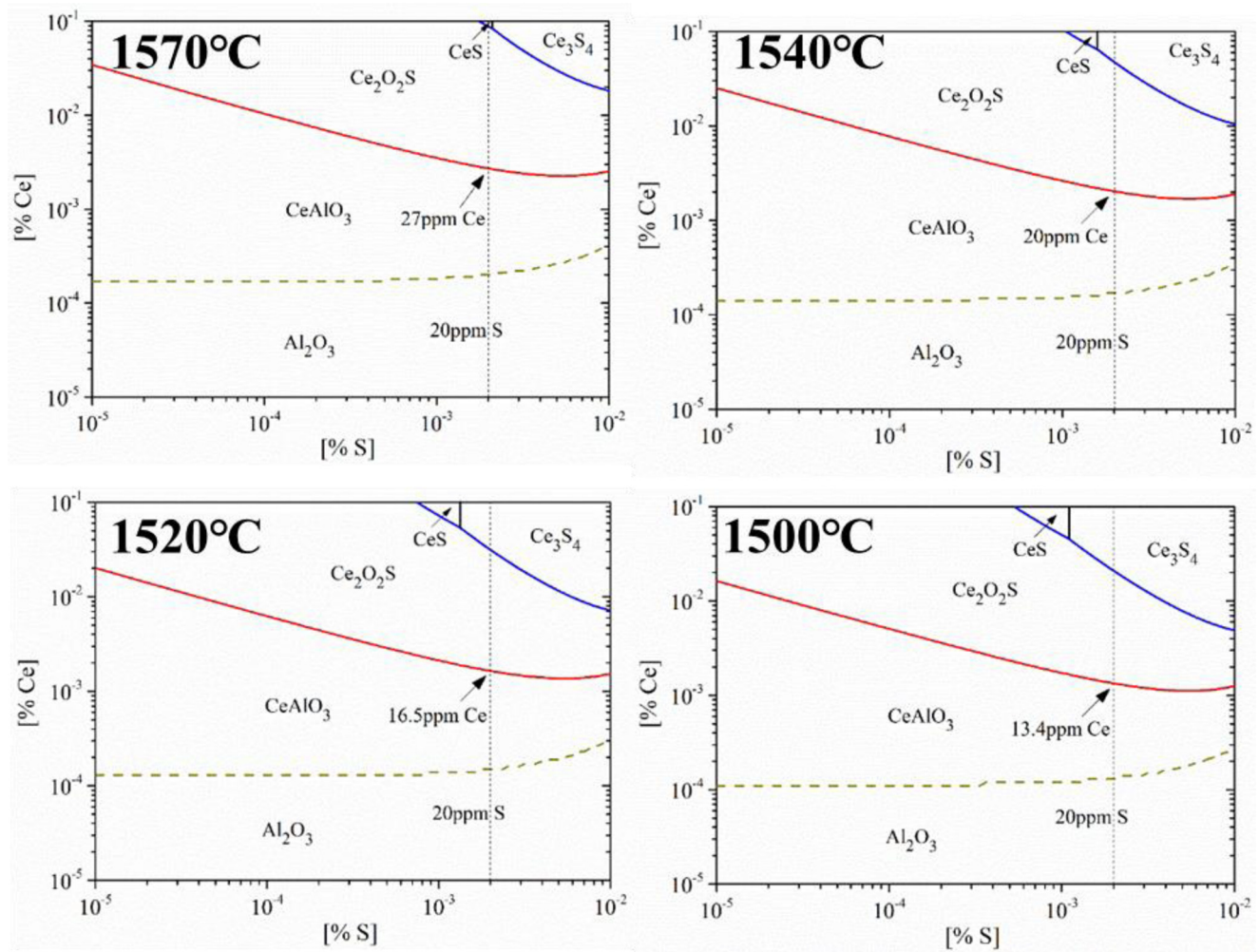


Fig. 6. [Ce]-[S] equilibrium diagram at different temperatures.

Table 2. [Ce] content corresponding to rare earth inclusion transformation ($[S] = 20 \text{ ppm}$).

Temperature, °C	$\text{Al}_2\text{O}_3 \rightarrow \text{CeAlO}_3$	$\text{CeAlO}_3 \rightarrow \text{Ce}_2\text{O}_2\text{S}$	$\text{Ce}_2\text{O}_2\text{S} \rightarrow \text{Ce}_x\text{S}_y$
1570	2.0	27.0	883
1540	1.7	20.0	472
1520	1.5	16.5	311
1500	1.3	13.4	208

The fr and fd of rare earth inclusions and typical inclusions in non-oriented silicon steel were calculated as shown in Table 5 (partially matched calculation results). The calculation results show that the mismatch between AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$ and LaAlO_3 , CeAlO_3 , $\text{La}_2\text{O}_2\text{S}$, $\text{Ce}_2\text{O}_2\text{S}$ along the close-packed crystal direction and the mismatch between crystal planes along the close-packed plane were less than 10%, which meet the empirical criterion of the E2EM model [47]. Therefore, LaAlO_3 , CeAlO_3 , $\text{La}_2\text{O}_2\text{S}$ and $\text{Ce}_2\text{O}_2\text{S}$ could be used as heterogeneous nucleation cores of AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$. Moreover, the minimum mismatch between AlN ,

Al_2O_3 and $\text{MgO-Al}_2\text{O}_3$ was all more than 10%, which does not meet the empirical criterion of the E2EM model.

However, according to the criteria of the E2EM model, the establishment of potential orientation relationships between the AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$ and the rare earth inclusions should meet some conditions. Such as, the matching crystallographic direction must lie on the matching lattice planes, and the matching of straight atomic rows should occur between straight atomic rows, while the matching of Z-type atomic rows should occur between Z-type atomic rows. Despite the criteria of the

Table 3. Main reactions of rare earth in non-oriented silicon steel [36].

Number	Chemical reactions	$\Delta G^0 = A + BT$, J/mol	
		A	B
[1]	$[Ce] + 3/2[O] = 1/2(Ce_2O_3)$	-715560	180
[2]	$[Ce] + [Al] + 3[O] = (CeAlO_3)$	-1366460	364.3
[3]	$[Ce] + [S] = (CeS)$	-42780	121
[4]	$[Ce] + 3/2[S] = 1/2(Ce_2S_3)$	-537290	164
[5]	$[Ce] + 4/3[S] = 1/3(Ce_3S_4)$	-498480	146
[6]	$2[Ce] + 2[O] + [S] = (Ce_2O_2S)$	-1353590	332
[7]	$[Ce] + (Al_2O_3) = (CeAlO_3) + [Al]$	-162837	-22.4
[8]	$[Ce] + [S] + (CeAlO_3) = (Ce_2O_2S) + [Al] + [O]$	12870	-32.3

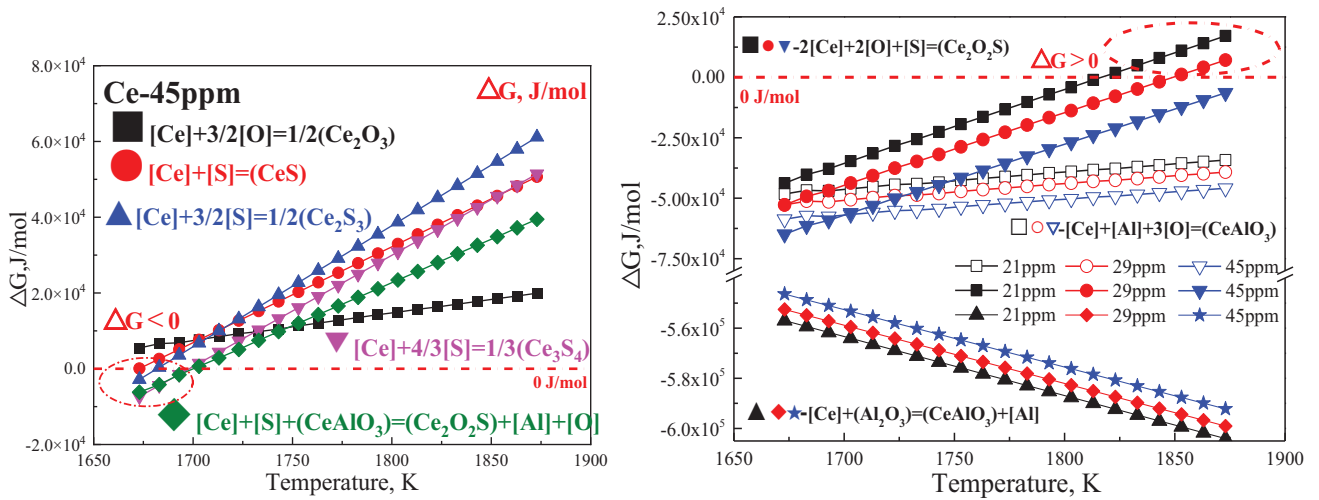
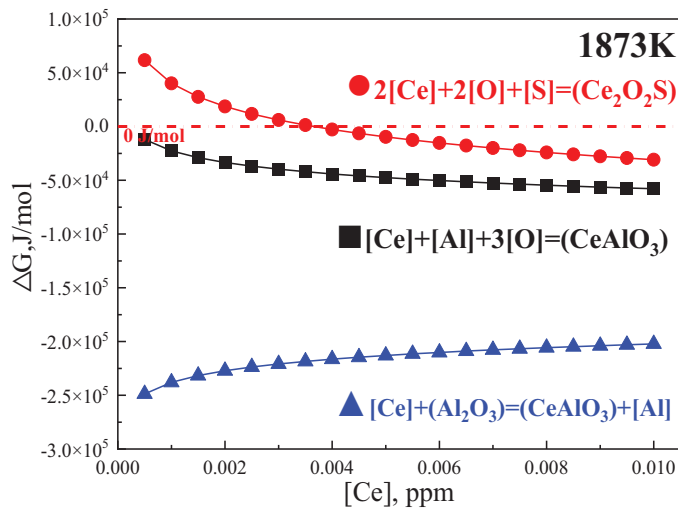
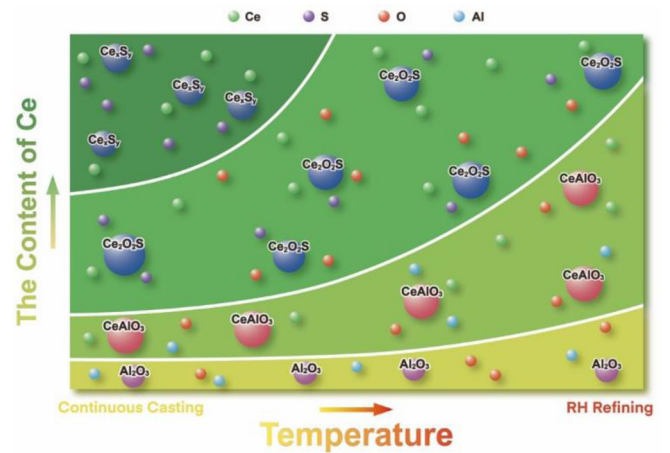
**Fig. 7.** ΔG of the chemical reactions.**Fig. 8.** Relationship between ΔG of main chemical reactions and Ce content at 1873 K.**Fig. 9.** Schematic diagram of inclusions in non-oriented silicon steel.

Table 4. Crystallographic data of LaAlO₃, CeAlO₃, La₂O₂S, Ce₂O₂S, AlN, Al₂O₃ and MgO-Al₂O₃ [40–44].

Phase	CP rows	Interatomic spcing/nm	Type	CP planes	Interplanar spcing/nm
LaAlO ₃	<110>	0.5361	SS	{111}	0.2189
	<100>	0.1896	SS	{110}	0.2681
	<111>	0.3283	SS	{100}	0.3791
	<110>	0.5402	SS	{111}	0.2205
CeAlO ₃	<100>	0.1910	SS	{110}	0.2701
	<111>	0.3308	SS	{100}	0.3802
	<1120>	0.4049	SS	{0002}	0.3470
	<1101>	0.3201	PS	{1011}	0.3130
La ₂ O ₂ S	<1010>	0.3507	ZZ	{1010}	0.3507
	<1123>	0.4017	ZZ	{1120}	0.2025
	<1120>	0.4001	SS	{0002}	0.3444
	<1101>	0.3223	PS	{1011}	0.3095
Ce ₂ O ₂ S	<1010>	0.3465	ZZ	{1010}	0.3465
	<1123>	0.3983	ZZ	{1120}	0.2001
	<1120>	0.3120	SS	{0002}	0.2494
	<1010>	0.2694	ZZ	{1011}	0.2376
AlN	<1123>	0.2889	ZZ	{1010}	0.2702
	<54 13>	0.310	PS	{0002}	0.6495
	<1101>	0.2750	SS	{1011}	0.3827
	<111>	0.6998	SS	{110}	0.5714
Al ₂ O ₃	<100>	0.5081	SS	{200}	0.3800
	<110>	1.1428	SS	{111}	0.4666
MgO-Al ₂ O ₃	<113>	0.4300	ZZ	{121}	0.3299

Table 5. Calculation results of mismatch.

Matching rows	Misfit (f_r)/%	Matching type	Matching planes	(f_d)/%
<1120>AlN//<111>LaAlO ₃	5.22	SS-SS	{0002}AlN//{110}LaAlO ₃	7.50
<1123>AlN//<113>LaAlO ₃	8.79	ZZ-ZZ	{1011}AlN//{111}LaAlO ₃	7.87
<1120>AlN//<111>CeAlO ₃	6.03	ZZ-ZZ	{1010}AlN//{110}LaAlO ₃	0.78
<1123>AlN//<113>CeAlO ₃	9.62	SS-SS	{0002}AlN//{110}CeAlO ₃	8.30
<1120>AlN//<1101>La ₂ O ₂ S	5.48	SS-PS	{1120}AlN//{1120}La ₂ O ₂ S	1.70
<1120>AlN//<1101>Ce ₂ O ₂ S	4.81	SS-PS	{1120}AlN//{1120}Ce ₂ O ₂ S	2.86
<5413>Al ₂ O ₃ //<111>LaAlO ₃	5.90	PS-SS	{1120}Al ₂ O ₃ //{111}LaAlO ₃	7.98
<5413>Al ₂ O ₃ //<111>CeAlO ₃	6.71	PS-SS	{1010}Al ₂ O ₃ //{100}CeAlO ₃	7.72
<5413>Al ₂ O ₃ //<1101>La ₂ O ₂ S	3.26	PS-PS	{1011}Al ₂ O ₃ //{1010}La ₂ O ₂ S	7.72
<5413>Al ₂ O ₃ //<1101>Ce ₂ O ₂ S	3.96	PS-PS	{1011}Al ₂ O ₃ //{1010}Ce ₂ O ₂ S	9.46
<1120>AlN//<111>MgO-Al ₂ O ₃	55.41	SS-SS	{1010}AlN//{121}MgO-Al ₂ O ₃	18.10
<5413>Al ₂ O ₃ //<111>MgO-Al ₂ O ₃	55.70	PS-SS	{1010}Al ₂ O ₃ //{200}MgO-Al ₂ O ₃	8.42
LaAlO ₃ //<100>MgO-Al ₂ O ₃	5.22	SS-SS	{100}LaAlO ₃ //{200}MgO-Al ₂ O ₃	0.24
CeAlO ₃ //<100>MgO-Al ₂ O ₃	5.94	SS-SS	{100}LaAlO ₃ //{200}MgO-Al ₂ O ₃	0.05
<1123>La ₂ O ₂ S//<113>MgO-Al ₂ O ₃	7.04	ZZ-ZZ	{1010}La ₂ O ₂ S//{200}MgO-Al ₂ O ₃	8.35
<1123>Ce ₂ O ₂ S//<113>MgO-Al ₂ O ₃	7.96	ZZ-ZZ	{1010}Ce ₂ O ₂ S//{200}MgO-Al ₂ O ₃	9.67

E2EM model, a rough prediction could be made regarding the orientation relationship between $(\text{La,Ce})\text{AlO}_3$, $(\text{La,Ce})_2\text{O}_3\text{S}$ and AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$.

Therefore, the computational results of the E2EM model and inclusions test results indeed point out that $(\text{La,Ce})\text{AlO}_3$ and $(\text{La,Ce})_2\text{O}_3\text{S}$ could effectively act as a nucleation core for AlN , Al_2O_3 and $\text{MgO-Al}_2\text{O}_3$, resulting in the formation of composite inclusions in Figure 2.

4 Conclusions

- Inclusions are mainly composite inclusions. $\text{La}+\text{Ce}$ would promote the spheroidization and coarsening of inclusions, and inclusions with irregular morphology would change to regular and near-circle morphology.
- Low content of rare earth (21ppm) mainly deoxidized and modified Al_2O_3 inclusions, and formed $(\text{La,Ce})\text{AlO}_3$ inclusions. Increasing of rare earth content (29–45 ppm) promoted the formation of $(\text{La,Ce})\text{AlO}_3$ – $(\text{La,Ce})_2\text{O}_3\text{S}$ and $(\text{La,Ce})_2\text{O}_3\text{S}$ inclusions and reduced the Sulfide precipitation, which agreed well with the thermodynamic analysis.
- 29–45 ppm rare earth had a weak metamorphic effect on Al_2O_3 inclusions, which was generated by temperature drop and secondary oxidation, and led to a gradual transition of the core of composite inclusions from $(\text{La,Ce})\text{AlO}_3$ to $(\text{La,Ce})\text{AlO}_3$ – $(\text{La,Ce})_2\text{O}_3\text{S}$ and $(\text{La,Ce})_2\text{O}_3\text{S}$.
- LaAlO_3 , CeAlO_3 , $\text{La}_2\text{O}_3\text{S}$ and $\text{Ce}_2\text{O}_3\text{S}$ could be the heterogeneous nucleation cores of AlN , Al_2O_3 , $\text{MgO-Al}_2\text{O}_3$, typical composite inclusions with $(\text{La,Ce})\text{AlO}_3$ and $(\text{La,Ce})_2\text{O}_3\text{S}$ as the cores would ultimately be generated.

Acknowledgments

Xinyu Iron and Steel Co., Ltd provided industrial trial support for this study

Funding

The authors acknowledge the support from the National Natural Science Foundation of China (NSFC) (No. 52374316), the Fund of Education Department of Anhui Province (No. 2022AH050291), the Open Project Program of Anhui Province Key Laboratory of Metallurgical Engineering & Resources Re-cycling (Anhui University of Technology) (No. SKF21-04 and SKF23-03) and the Jiangxi Province Major Scientific and Technological Research and Development Special Funding Project (20213AAE01009).

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

This article has no associated data generated and/or analyzed / Data associated with this article cannot be disclosed due to legal/ethical/other reason.

Author contribution statement

Conceptualization, Haijun Wang and Kaixuan Shao ; Methodology, Yuhao Niu; Software, Kaixuan Shao; Validation, Haijun Wang, Kaixuan Shao and Jialong Qiao; Formal Analysis, Jialong Qiao; Investigation, Hongbo Pan; Resources, Yuhao Niu; Data Curation, Kaixuan Shao; Writing – Original Draft Preparation, Kaixuan Shao; Writing – Review & Editing, Jialong Qiao; Visualization, Hongbo Pan; Supervision, Sheng-tao Qiu; Project Administration, Shengtao Qiu; Funding Acquisition, Shengtao Qiu”.

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Cite this article as: Haijun Wang, Kaixuan Shao, Yuhao Niu, Jialong Qiao, Hongbo Pan, Shengtao Qiu, Influence mechanism of rare earth (RE) on inclusion modification in non-oriented silicon steel, *Metall. Res. Technol.* **121**, 604 (2024)