

Article

Evolution and Formation of Non-Metallic Inclusions during Electroslag Remelting of Ce-Bearing 15Cr-22Ni-1Nb Austenitic Heat-Resistant Steel

Zhongwei Wang, Chengbin Shi * , Shijun Wang, Jing Li and Xin Zhu

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing (USTB), Beijing 100083, China

* Correspondence: chengbin.shi@ustb.edu.cn

Abstract: The evolution of inclusions in austenitic heat-resistant steel with different Ce content during protective argon gas atmosphere electroslag remelting (ESR) was studied. All oxide inclusions in the Ce-free consumable electrode are $\text{MgO} \cdot \text{Al}_2\text{O}_3$. A part of these $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions was removed before metal droplets entered the liquid metal pool during the ESR. The soluble oxygen (arising from the reoxidation) reacted with soluble aluminum, calcium, and magnesium in liquid steel to form $\text{MgO} \cdot \text{Al}_2\text{O}_3$ and $\text{CaO} \cdot \text{Al}_2\text{O}_3$ inclusions in liquid steel. All oxide inclusions in the electrode with 0.016 mass% Ce are Ce_2O_3 . A portion of these Ce_2O_3 inclusions was dissociated into soluble oxygen, cerium, and sulfur in liquid steel during the ESR process, whereas the others were removed by absorbing them into molten slag. The oxide inclusions in the liquid metal pool and remelted ingot were Ce_2O_3 , CeAlO_3 , and $\text{Ce}_2\text{O}_2\text{S}$. The CeAlO_3 and Ce_2O_3 inclusions were reoxidation products formed by the chemical reaction between the soluble oxygen, soluble aluminum, and cerium. The oxide inclusions in the electrode with 0.300 mass% Ce are CeS and $\text{Ce}_2\text{O}_2\text{S}$. These CeS inclusions were removed by molten slag adsorption during the ESR. A part of these $\text{Ce}_2\text{O}_2\text{S}$ inclusions was removed by slag adsorption, and the remaining entered into the liquid metal pool. The oxide inclusions in the liquid metal pool and the ingot were Ce_2O_3 and $\text{Ce}_2\text{O}_2\text{S}$. The Ce_2O_3 inclusions were formed through the chemical reaction between the soluble oxygen and cerium in the liquid metal pool. The $\text{Ce}_2\text{O}_2\text{S}$ inclusions in the liquid pool originate from reoxidation products during the ESR process and the relics from the electrode.

Keywords: inclusion; cerium; electroslag remelting; reoxidation; evolution

Citation: Wang, Z.; Shi, C.; Wang, S.; Li, J.; Zhu, X. Evolution and Formation of Non-Metallic Inclusions during Electroslag Remelting of Ce-Bearing 15Cr-22Ni-1Nb Austenitic Heat-Resistant Steel. *Metals* **2022**, *12*, 2094. <https://doi.org/10.3390/met12122094>

Academic Editors: Mark E. Schlesinger and Antoni Roca

Received: 28 October 2022

Accepted: 5 December 2022

Published: 6 December 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Austenitic heat-resistant steel of Ni-Cr system is extensively utilized in automotive engines and fossil fuel power generation plants applications at moderately elevated temperatures, such as fasteners and bolts, and heat exchangers, because of their superior strength, toughness, oxidation resistance, and organizational stability [1–3]. Except the advantages of some types of fine non-metallic inclusions through acting as the nucleation sites to generate intragranular acicular ferrites and the pinning particles to inhibit the growth of austenite grains [4], inclusions are generally detrimental to mechanical properties of steel, such as creep strength, fatigue strength, corrosion resistance, tensile properties, toughness, and ductility [5–10]. The local stress concentration induced by large inclusions often causes cracking at inclusion-steel matrix interface during working of steel [11]. The detriment degree of inclusions is strongly dependent on their number density, size, and chemical compositions.

Rare earth Ce can improve the corrosion resistance [12,13], oxidation resistance [14,15], grain refinement [16,17] and reduction of dendritic spacing [18,19] of heat-resistant steels and improve the mechanical properties of austenitic heat-resistant steels [20,21]. The generation of Ce-bearing non-metallic inclusions in Ce-containing steel was unavoidable. Ce-containing inclusions were detrimental to the fatigue strength, toughness and ductility,

impact strength, tensile properties, corrosion resistance, initiation of fatigue cracking, and stress concentration cracking of steel [22–24]. Many studies on the evolution of Ce-bearing inclusions have been conducted in industrial-scale secondary refining (LF and RH refining) or laboratory-scale crucible experiments of slag-steel reactions [25,26]. However, no studies have been reported on the evolution of Ce-bearing inclusions in the ESR process.

In the current study, the evolution of inclusions in the steel with different Ce contents during ESR was investigated. The effect of reoxidation during the ESR on inclusion evolution was ascertained. The evolution mechanism of Ce-bearing inclusions during the ESR was elucidated.

2. Experimental

2.1. ESR Experimental Procedure

The chemical compositions of the consumable electrodes are shown in Table 1. The oxide scale on the electrode steel surface was thoroughly removed before ESR experiments. The pre-melted slag (40.92 mass% CaF_2 , 27.09 mass% CaO , 0.52 mass% MgO , 29.02 mass% Al_2O_3 , 0.92 mass% SiO_2 , 0.21 mass% FeO) was roasted at 700 °C (973 K) for 8 h to remove moisture before the ESR trials.

Table 1. Chemical compositions of the consumable electrodes (mass%).

Trials No.	C	Si	Mn	Mo	Ti	Cr	Ni	Al	Nb	S	Ca	Ce	Mg	N	O
T1	0.02	0.5	0.83	2.49	0.18	15.1	22	0.15	0.98	0.0032	0.0002	0	0.0004	0.0071	0.0010
T2	0.02	0.5	0.89	2.53	0.14	14.9	22	0.10	0.99	0.0009	0.0002	0.016	0.0003	0.0120	0.0006
T3	0.02	0.5	0.78	2.50	0.21	14.6	22	0.15	1.03	0.0025	0.0002	0.300	0.0003	0.0031	0.0007

Three ESR trials were conducted in protective argon gas atmosphere. The operating current, voltage, and outlet temperature of the mold cooling water were maintained at about 2500 A, 32 V, and 313 K. During electroslag remelting of the steel electrode with 0.016 mass% Ce, Al shots were added for deoxidation (addition amount: 1 kg/ton of steel). For deoxidation in ESR trial T3, Al shots were added (2 kg/ton of steel) during the ESR of the electrode with 0.300 mass% Ce. A steel sample was taken from the liquid metal pool during the ESR refining using a vacuum sampling tube made of quartz, followed by quenching in water. The remelted ingots corresponding to the ESR trials T1, T2, and T3 were designated as ingots C1, C2, and C3, respectively.

2.2. Compositional Analysis and Inclusions Characterization

The steel samples were taken from the consumable electrodes and the remelted ingots of the ESR for chemical composition analysis. The total oxygen (composed of both the soluble oxygen and the oxygen bonded as oxide inclusions) content of the steel was measured by the inert gas fusion-infrared absorptiometry. The sulfur and carbon contents of the steel were measured by the combustion-infrared absorption technique. The nitrogen content was determined by the inert gas fusion-thermal conductivity method. The contents of soluble aluminum, total calcium, magnesium, silicon, cerium, and manganese in the electrodes and ingots were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Steel samples for metallographic observation were taken from the consumable electrodes and the mid-height of each remelted ingot at the mid-radius position. To reveal the evolution of inclusions in the ESR process, steel samples collected from the liquid metal pool with vacuum sampling tubes were polished after mechanical grinding. Inclusions exposed on the cross-section of the polished sample were analyzed in terms of their chemistry, size, and morphology by scanning electron microscope (SEM; FEI Quanta-250, FEI Corp, Hillsboro, OR, USA) equipped with an energy-dispersive X-Ray spectrometer (EDS, XFlash 5030; Bruker, Karlsruhe, Germany).

Furthermore, the size of inclusions on the polished sample cross-section was calculated using the equivalent circle diameter (ECD). The equivalent circle diameter of the inclusions smaller than 1 μm is not included in analysis.

3. Results and Discussion

3.1. Steel Composition

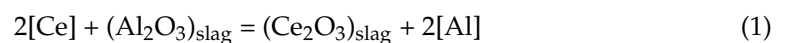
The chemical compositions of remelted ingots are shown in Table 2. The Ce contents of the remelted ingots C2 and C3 are 0.0055 mass% and 0.063 mass%, respectively. The yields of Ce during the ESR are 34.4% and 21.0%, respectively.

Table 2. Chemical Compositions of Remelted Ingots (mass%).

Ingot No.	C	Si	Mn	Mo	Ti	Cr	Ni	Al	Nb	S	Ca	Ce	Mg	N	O
C1	0.02	0.5	0.82	2.60	0.13	15.5	22	0.19	1.00	0.0007	0.0002	0	0.0004	0.0076	0.0016
C2	0.02	0.5	0.89	2.60	0.12	15.4	22	0.23	1.00	0.0007	0.0002	0.0055	0.0003	0.0140	0.0013
C3	0.02	0.5	0.83	2.50	0.15	14.6	22	0.15	1.02	0.0016	0.0002	0.0630	0.0003	0.0054	0.0018

The aluminum content of the steel increases from 0.15 mass% in the Ce-free electrode to 0.19 mass% in the remelted ingot C1. The aluminum content of steel in the ESR trial T2 increases from 0.10 mass% in the consumable electrode to 0.23 mass% in the ingot C2. The aluminum content of the steel in the ESR trial T3.

The slag-steel reactions during the ESR are a potential source of soluble aluminum pickup in liquid steel. The chemical reaction between Ce in liquid steel and Al_2O_3 in the slag can be expressed as follows [27]:



$$\Delta G^\circ = 205703 + 34T \text{ (J/mol)} \quad (2)$$

$$K = \frac{a_{\text{Al}}^2 \cdot a_{\text{Ce}_2\text{O}_3}}{a_{\text{Ce}}^2 \cdot a_{\text{Al}_2\text{O}_3}} = \frac{(f_{\text{Al}}[\% \text{Al}])^2 \cdot a_{\text{Ce}_2\text{O}_3}}{(f_{\text{Ce}}[\% \text{Ce}])^2 \cdot a_{\text{Al}_2\text{O}_3}} \quad (3)$$

where $a_{\text{Ce}_2\text{O}_3}$ and $a_{\text{Al}_2\text{O}_3}$ are the activities of Ce_2O_3 and Al_2O_3 in the slag, respectively. f_{Al} and f_{Ce} are the activity coefficients of soluble aluminum and Ce in the liquid alloy, respectively, which can be calculated by the following equation [28].

$$\lg f_i = \sum e_i^j [\%j] \quad (4)$$

where e_i^j is the first-order interaction parameter.

The activities of the Al_2O_3 and Ce_2O_3 relative to pure solid standard states in the slag melts at 1873 K (1600 °C) are estimated with FactSage 8.0 (FToxid database; ThermFact/CRCT, Montreal, Canada). According to the chemical composition of the electrode with 0.300 mass% Ce combined with the first-order interaction parameters (as shown in Table 3), the Gibbs free energy change for the chemical reaction (1) was calculated to be 312.89 kJ/mol. It suggests that Ce in the electrode with 0.300 mass% Ce cannot reduce the Al_2O_3 in the slag during the ESR process, leading to the Al pickup in the steel. The Al pickup in liquid steel is caused by the Al addition in the ESR process.

Table 3. First-order interaction parameters used in the current study [29–32].

	C	Si	Mn	Mo	Ti	Cr	Ni	Al	Mg	Ca	S	Ce	N	O
O	−0.421	−0.066	−0.021	0.005	−1.8	−0.033	0.006	−1.17	−300	−	−0.133	−0.57	0.057	−0.17
S	0.111	0.075	−0.026	−	−0.27	−0.0105	−	0.041	−1.82	−110	−0.046	−1.91	0.01	−0.27
Al	0.091	0.056	0.035	−	0.004	−	−0.029	0.045	−0.3	−0.047	0.035	−0.52	−0.057	−1.98
Ce	−0.077	−	−	−	−3.62	−	−	−2.25	−	−	−8.36	−0.003	−6.612	−5.03

In the present study, the oxygen contents of the electrodes with different Ce contents apparently increase during the ESR to 0.0016 mass%, 0.0013 mass%, and 0.0018 mass% in ingots C1, C2, and C3, respectively. It indicates that the reoxidation of the liquid steel occurred in these three ESR trials. The sulfur contents of steel decrease during the ESR to 0.0007 mass%, 0.0007 mass%, and 0.0016 mass% in ingots C1, C2, and C3, respectively.

The difference in the oxygen potential between liquid steel with low oxygen content and the molten slag contributes to soluble oxygen pickup in liquid steel during the protective argon gas atmosphere ESR [33]. The introduction of FeO (newly formed FeO during ESR and the unremoved oxide layer on the surface of the electrode steel) to the molten slag pool during ESR is difficult to be prevented, and it is the source of the increased oxygen content of liquid steel according to the chemical reaction $(\text{FeO})_{\text{slag}} = [\text{Fe}] + [\text{O}]$ ($\Delta G^\circ = -139,000 + 57.1T$ (J/mol)) [34].

The interaction coefficients used in the present calculation are shown in Table 3. The Gibbs free energy change for the chemical reaction $(\text{FeO})_{\text{slag}} = [\text{Fe}] + [\text{O}]$ for the ESR trials T1, T2, and T3 was calculated to be -102.75 kJ/mL, -105.99 kJ/mL, and -100.92 kJ/mL, respectively. It indicates that FeO in molten slag transfers oxygen to liquid steel, resulting in the reoxidation of liquid steel during ESR. Meanwhile, the desulfurization reaction $(\text{CaO}) + [\text{S}] = (\text{CaS})_{\text{slag}} + [\text{O}]$ is also an important source of soluble oxygen pickup in the liquid steel during the ESR [35].

3.2. Inclusions in Consumable Steel Electrode

The SEM images and EDS spectra of typical inclusions in the consumable electrodes are shown in Figures 1–5. As shown in Figure 1, the typical inclusions in the Ce-free electrode are $(\text{Ti,Nb})\text{N}$, $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions surrounded by $(\text{Ti,Nb})\text{N}$ and $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions, respectively. Figure 1a shows typical $(\text{Ti,Nb})\text{N}$ inclusions in the electrode with near-square shape. Figure 1c,d show typical $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions in Ce-free electrode, and the morphology of these spinel inclusions is nearly spherical. The $\text{MgO} \cdot \text{Al}_2\text{O}_3$ spinel inclusion plays a nucleation role for $(\text{Ti,Nb})\text{N}$.

Figures 2 and 3 show the typical inclusions in the electrode with 0.016 mass% Ce. The observed inclusions are $(\text{Ti,Nb})\text{N}$, and $\text{Ce}_2\text{O}_3\text{S}$, respectively. Figure 2a shows typical inclusions $(\text{Ti,Nb})\text{N}$ in the consumable electrode with a clear angular shape. Figure 2b,c show the typical inclusions of $\text{Ce}_2\text{O}_3\text{S}$ in the consumable electrode, showing both near spherical or irregular morphologies.

The typical inclusions in the electrode with 0.300 mass% Ce are shown in Figures 4 and 5. The rare-earth inclusions in the electrode are identified as CeS and $\text{Ce}_2\text{O}_3\text{S}$, respectively. It can be seen from SEM photographs that these inclusions are near-spherical. It is found from ESD element mappings of the $\text{Ce}_2\text{O}_3\text{S}$ inclusion that the elements are uniformly distributed on cross-section of the inclusions.

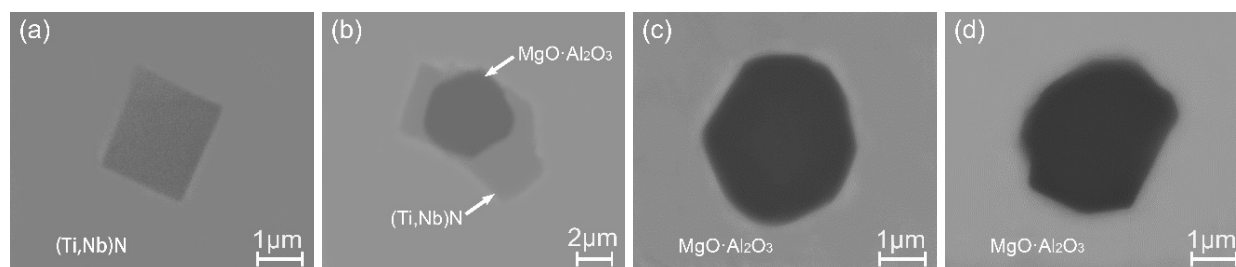


Figure 1. Typical inclusions in the Ce-free electrode. (a) $(\text{Ti,Nb})\text{N}$, (b) $\text{MgO} \cdot \text{Al}_2\text{O}_3 + (\text{Ti,Nb})\text{N}$, (c) and (d) $\text{MgO} \cdot \text{Al}_2\text{O}_3$.

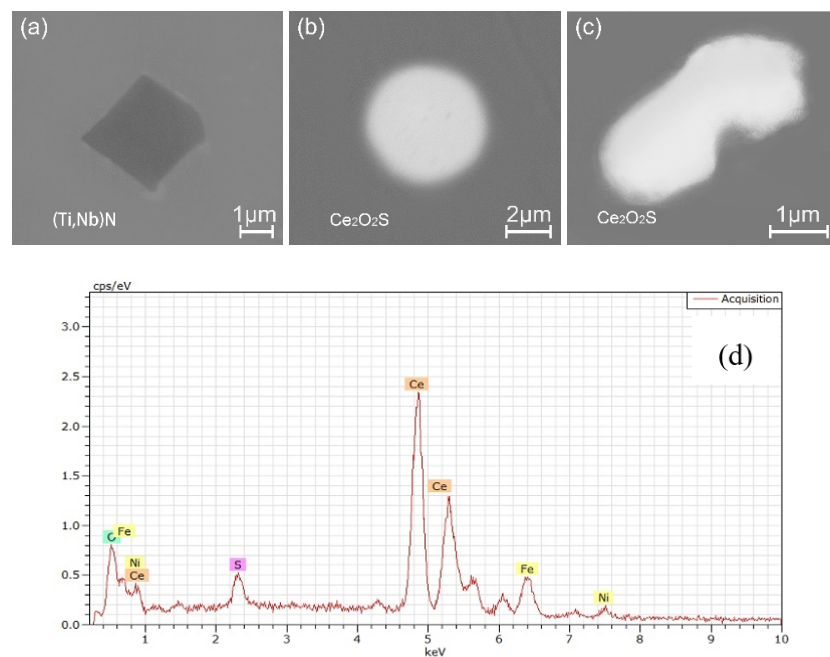


Figure 2. SEM images and EDS spectra of typical inclusions in the electrode with 0.016 mass% Ce. (a) (Ti,Nb)N, (b,c) $\text{Ce}_2\text{O}_2\text{S}$. (EDS spectrum shown in (d) corresponds to the inclusion shown in (c)).

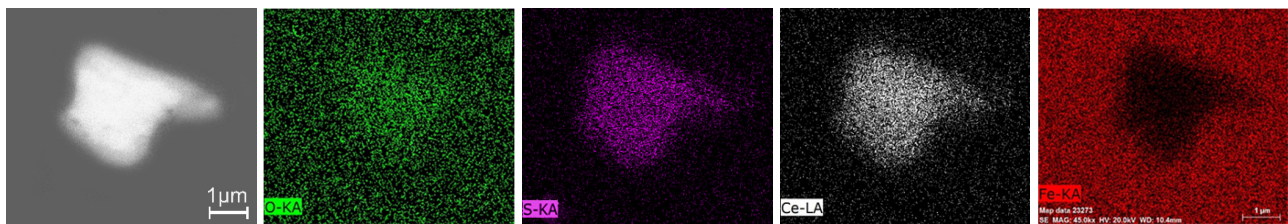


Figure 3. EDS element mappings of $\text{Ce}_2\text{O}_2\text{S}$ inclusion in the electrode with 0.016 mass% Ce.

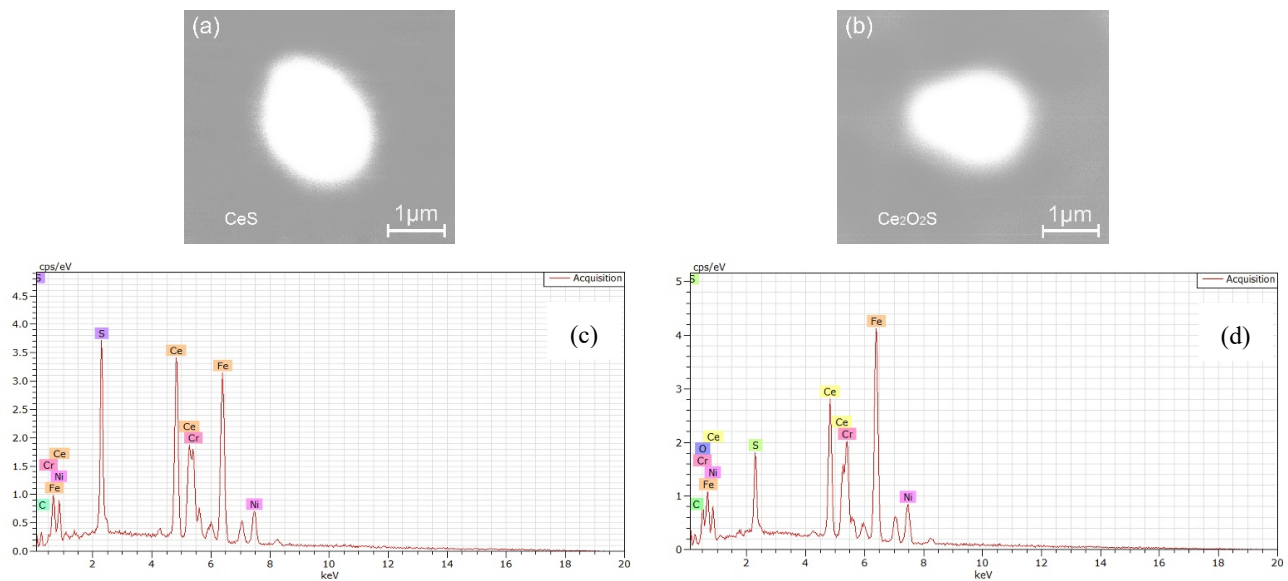


Figure 4. SEM images and EDS spectra of typical inclusions in the electrode with 0.300 mass% Ce. (a) CeS, (b) $\text{Ce}_2\text{O}_2\text{S}$. (EDS spectra shown in (c) and (d) correspond to the inclusions shown in (a) and (b), respectively).

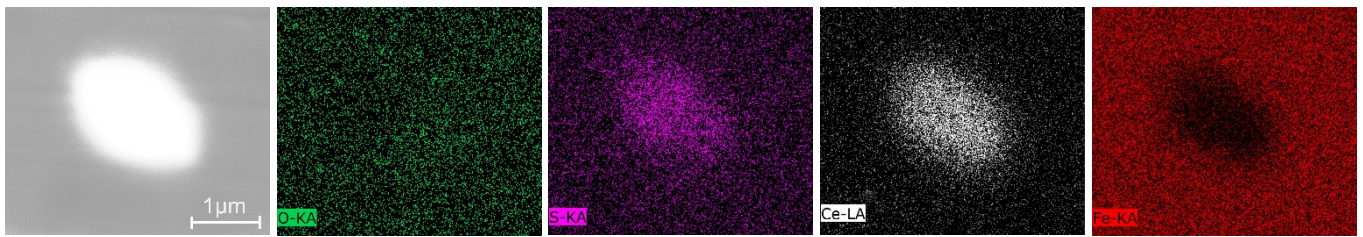


Figure 5. EDS element mappings of $\text{Ce}_2\text{O}_2\text{S}$ inclusion in the electrode with 0.300 mass% Ce.

3.3. Inclusions in the Liquid Metal Pool and Remelted Ingots

The SEM micrographs, EDS spectra, and elemental mappings of typical inclusions observed in the liquid metal pool during the ESR trial T1 and remelted ingot C1 are shown in Figures 6–9. The inclusions in the liquid metal pool of the ESR trial T1 are $(\text{Ti,Nb})\text{N}$, $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions wrapped by $(\text{Ti,Nb})\text{N}$, $\text{CaO} \cdot \text{Al}_2\text{O}_3$, and $\text{MgO} \cdot \text{Al}_2\text{O}_3$.

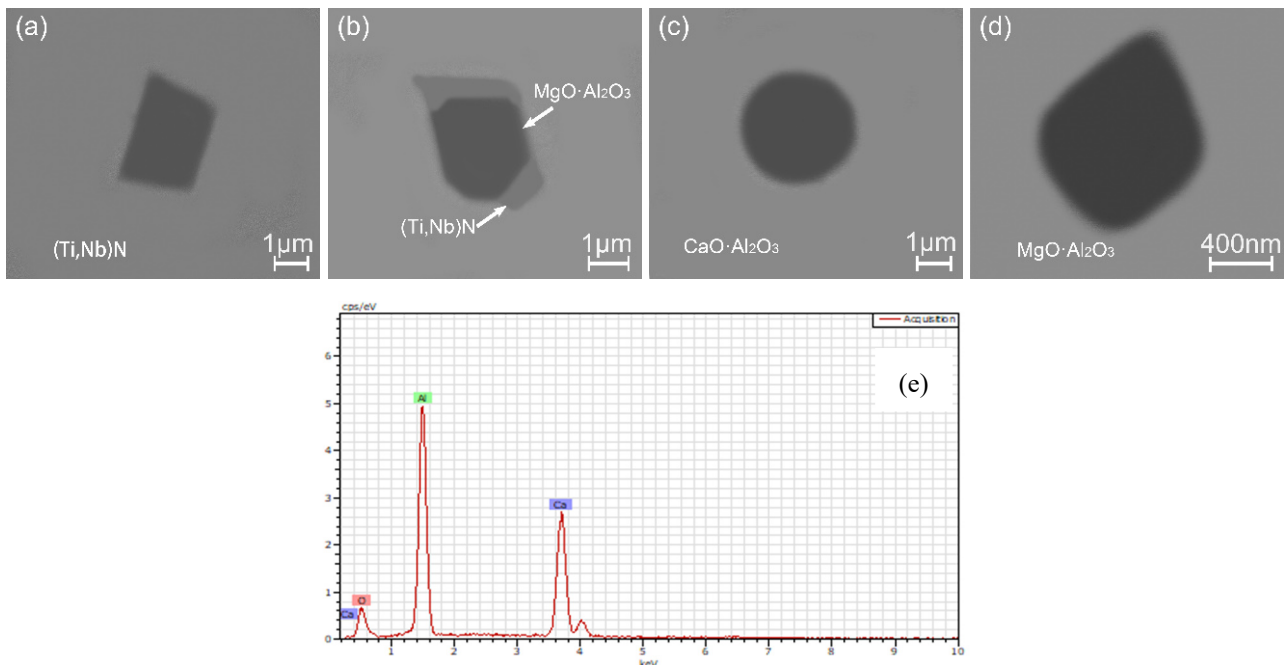


Figure 6. SEM images and EDS spectra of inclusions in the liquid metal pool during ESR trial T1. (a) $(\text{Ti,Nb})\text{N}$, (b) $\text{MgO} \cdot \text{Al}_2\text{O}_3 + (\text{Ti,Nb})\text{N}$, (c) $\text{CaO} \cdot \text{Al}_2\text{O}_3$, (d) $\text{MgO} \cdot \text{Al}_2\text{O}_3$. (EDS spectrum shown in (e) corresponds to the inclusion shown in (c)).

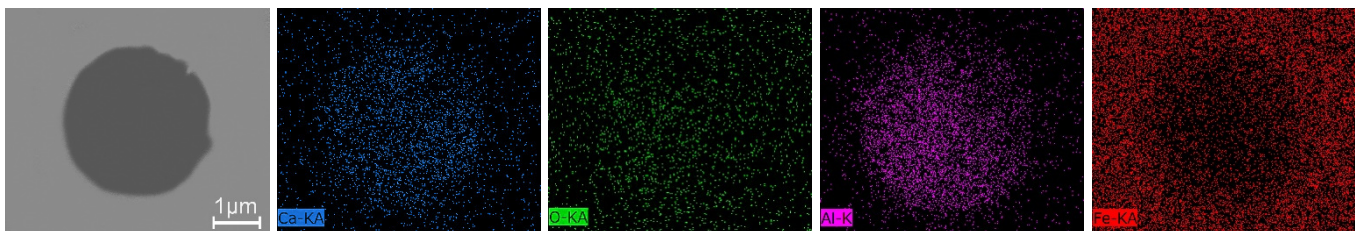


Figure 7. EDS element mappings of $\text{CaO} \cdot \text{Al}_2\text{O}_3$ inclusion in the liquid metal pool during the ESR trial T1.

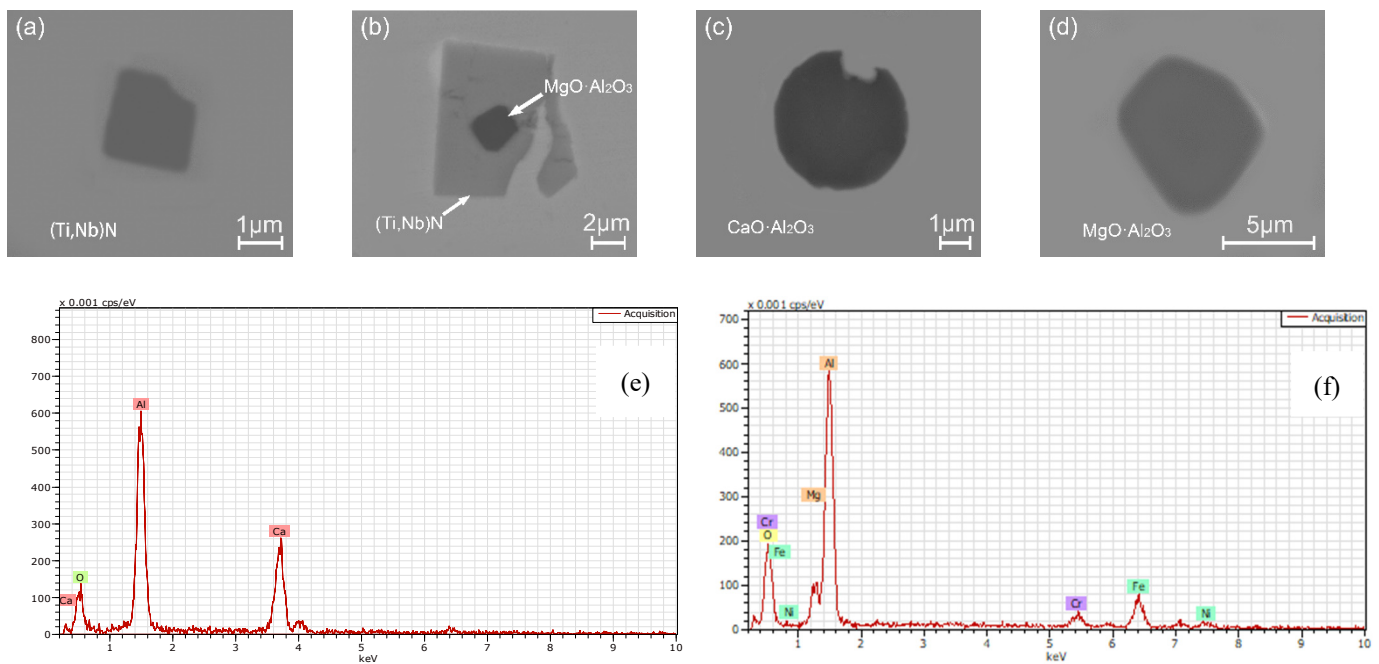


Figure 8. SEM images and EDS spectra of typical inclusions observed in ingot C1. (a) (Ti,Nb)N, (b) $\text{MgO} \cdot \text{Al}_2\text{O}_3$ + (Ti,Nb)N, (c) $\text{CaO} \cdot \text{Al}_2\text{O}_3$, (d) $\text{MgO} \cdot \text{Al}_2\text{O}_3$. (EDS spectra shown in (e) and (f) correspond to the inclusions shown in (c) and (d), respectively).

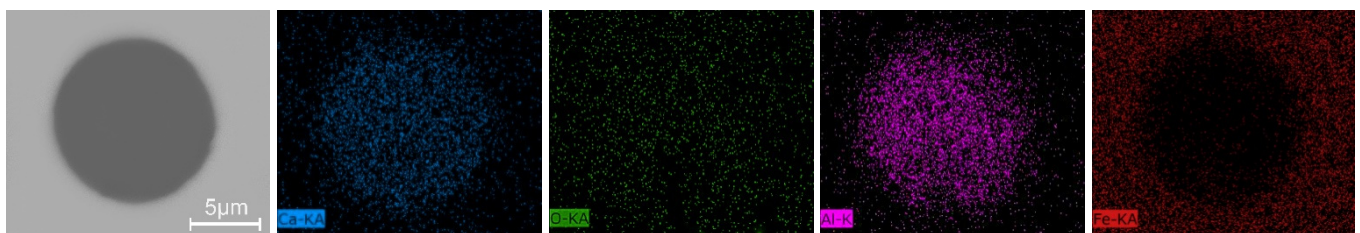


Figure 9. EDS element mappings of $\text{CaO} \cdot \text{Al}_2\text{O}_3$ inclusion in the ingot C1.

Four types of inclusions are found in ingot C1, namely (Ti,Nb)N inclusions, $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions wrapped by (Ti,Nb)N, $\text{CaO} \cdot \text{Al}_2\text{O}_3$, and $\text{MgO} \cdot \text{Al}_2\text{O}_3$. Figures 7 and 9 show the EDS element mappings of $\text{CaO} \cdot \text{Al}_2\text{O}_3$ inclusions in the liquid metal pool of the ESR trial T1 and remelted ingot C1, respectively. CaO and Al_2O_3 are uniformly distributed over the entire cross-section of the inclusion.

SEM micrographs, EDS spectra, and elemental mappings of typical inclusions in the liquid metal pool of ESR trial T2 and remelted ingot are shown in Figures 10–13. The types of inclusions in the liquid metal pool of the ESR trial T2 are (Ti,Nb)N, $\text{Ce}_2\text{O}_3\text{S}$, and CeAlO_3 encapsulated by (Ti,Nb)N, CeAlO_3 , and Ce_2O_3 . The types of inclusions are (Ti,Nb)N, $\text{Ce}_2\text{O}_3\text{S}$, CeAlO_3 surrounded by (Ti,Nb)N, and Ce_2O_3 . It is observed that the types of inclusions in the remelted ingot did not change compared to the types of inclusions in the liquid metal pool.

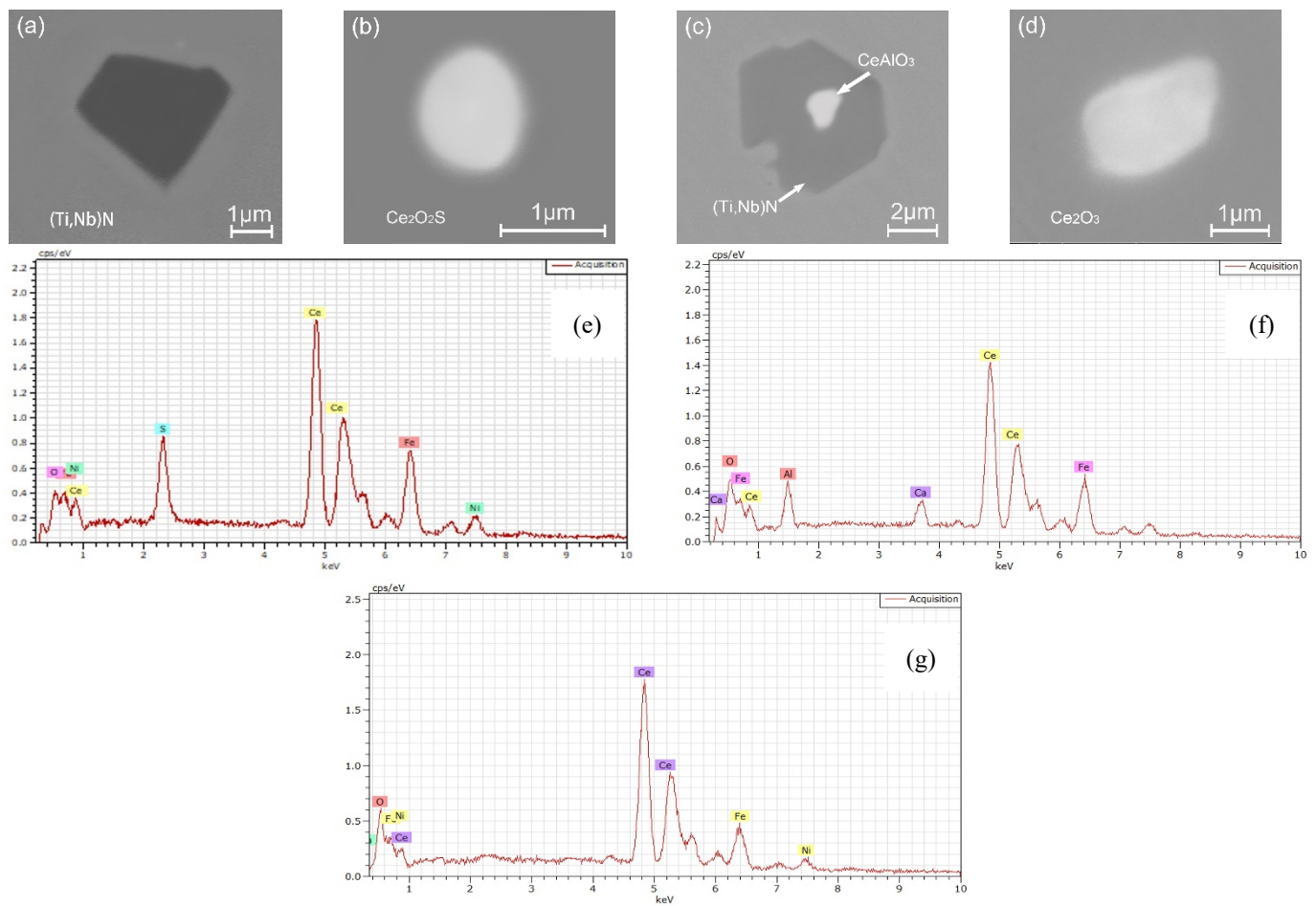


Figure 10. SEM images and EDS spectra of typical inclusions in the liquid metal pool during the ESR trial T2. (a) (Ti,Nb)N, (b) $\text{Ce}_2\text{O}_2\text{S}$, (c) $\text{CeAlO}_3 + (\text{Ti,Nb})\text{N}$, (d) Ce_2O_3 . (EDS spectra shown in (e), (f) and (g) correspond to the inclusions shown in (b), (c) and (d), respectively).

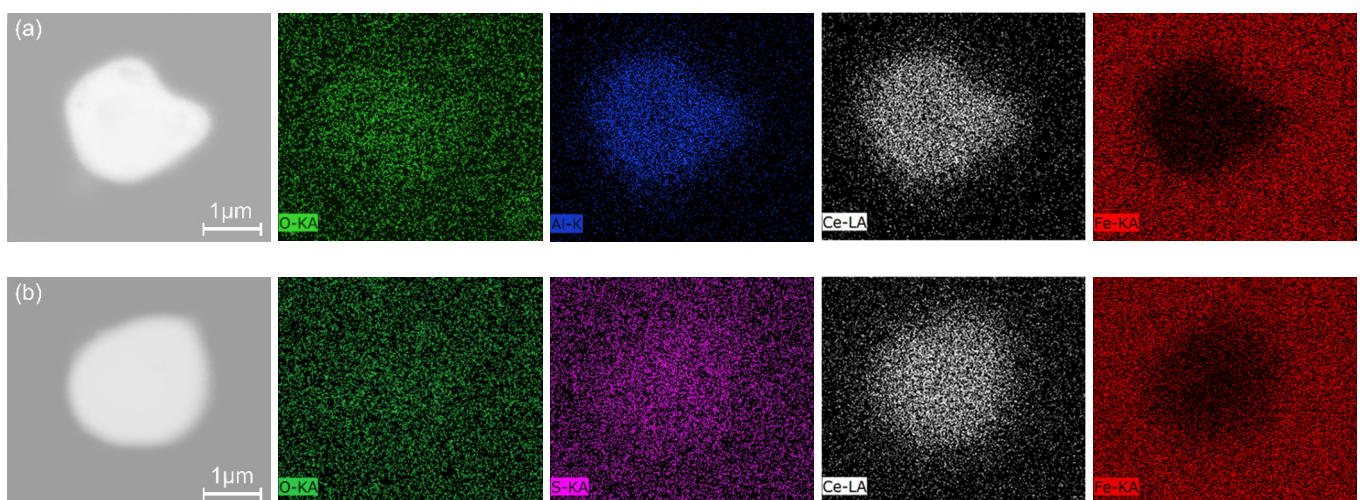


Figure 11. EDS element mappings of CeAlO_3 and $\text{Ce}_2\text{O}_2\text{S}$ inclusions in the liquid metal pool during the ESR trial T2. (a) CeAlO_3 (b) $\text{Ce}_2\text{O}_2\text{S}$.

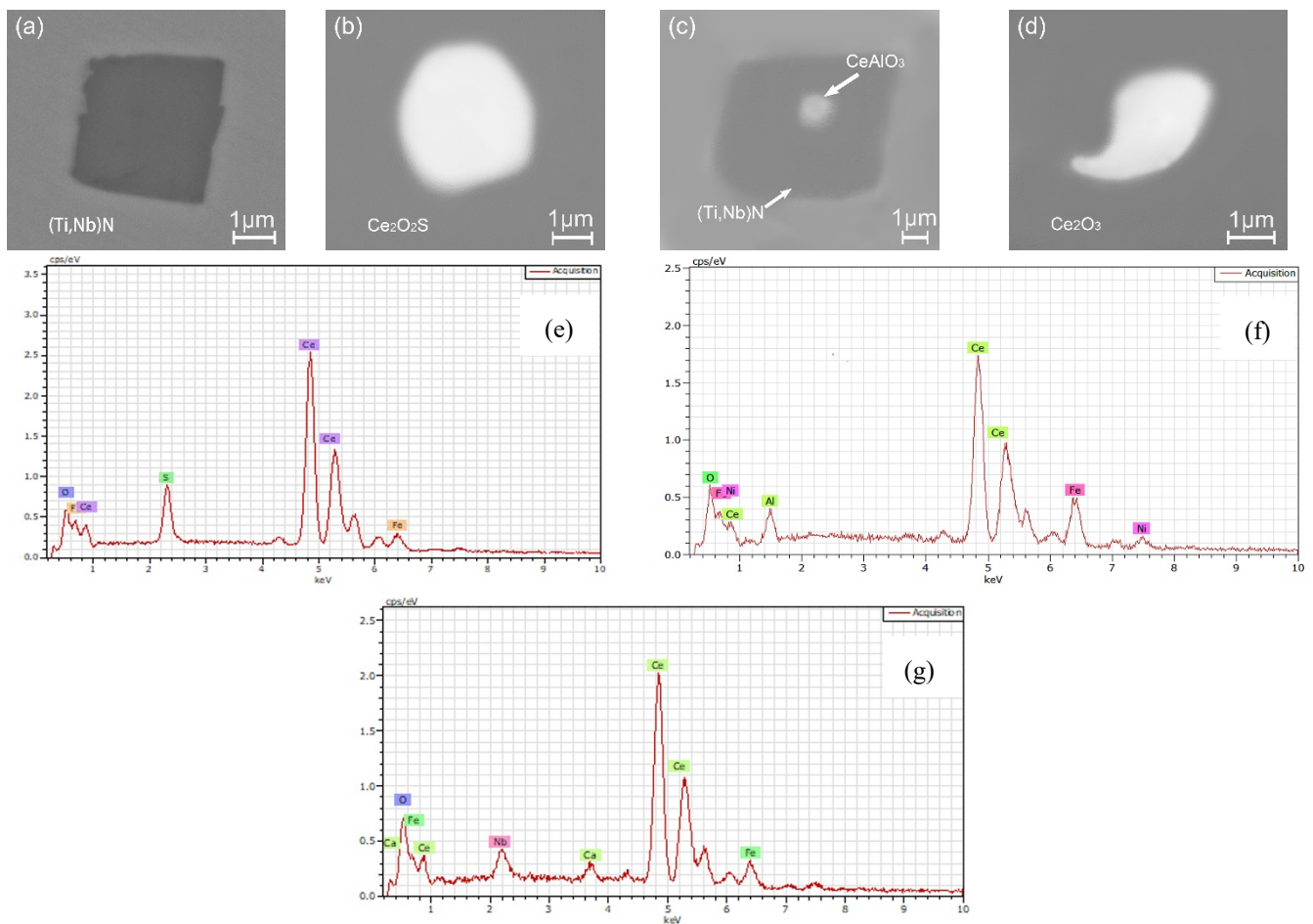


Figure 12. SEM images and EDS spectra of typical inclusions in the ingot C2. (a) (Ti,Nb)N, (b) Ce₂O₂S, (c) CeAlO₃ + (Ti,Nb)N, (d) Ce₂O₃. (EDS spectra shown in (e,f), and (g) correspond to the inclusions shown in (b,c), and (d), respectively).

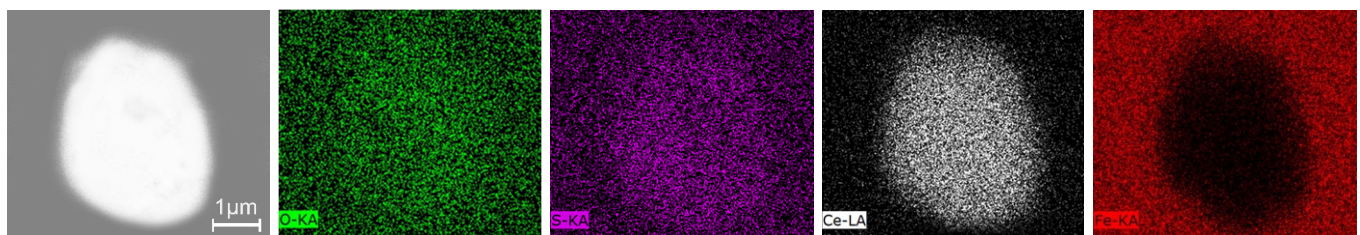


Figure 13. EDS element mappings of Ce₂O₂S inclusion in the ingot C2.

Typical inclusions in the liquid metal pool and remelted ingot for the ESR trial T3 are shown in Figures 14–17. The two types of rare earth inclusions in the liquid metal pool of the ESR trial T3 are observed to be Ce₂O₃ and Ce₂O₂S, and the morphology of these rare-earth inclusions is near-spherical. The results of the elements mappings of Ce₂O₂S inclusions in the liquid metal pool of ESR trial T3 and remelted ingot are shown in Figures 11 and 13, respectively.

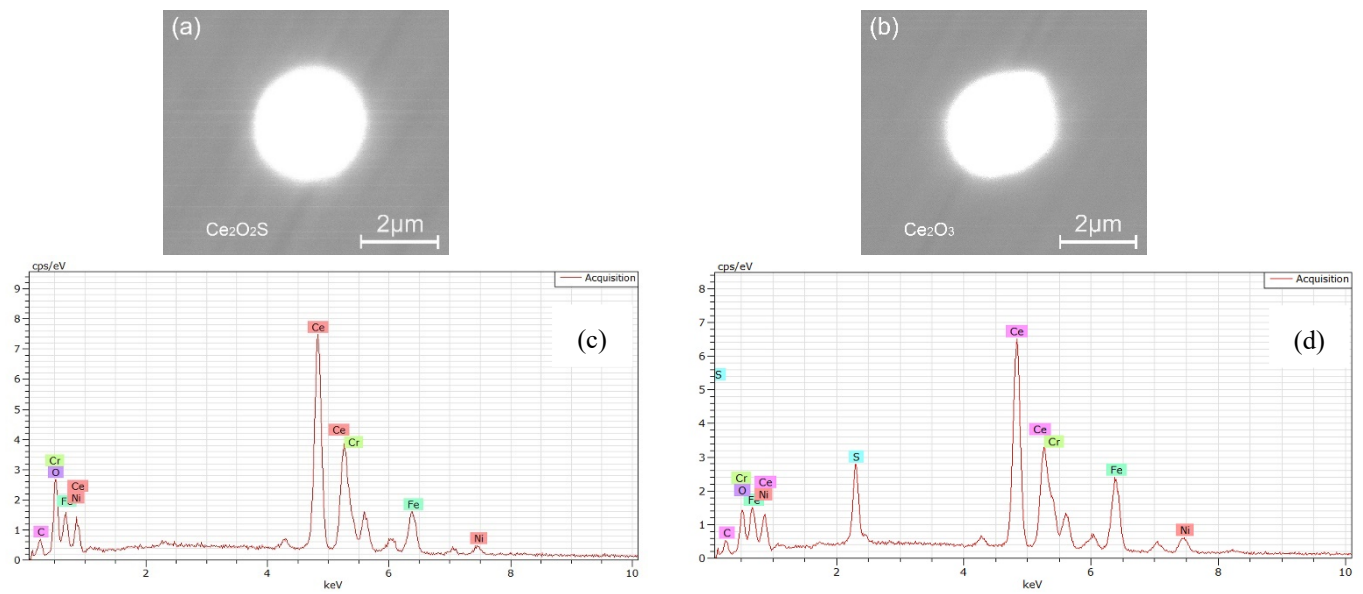


Figure 14. SEM images and EDS spectra of typical inclusions in the liquid metal pool during ESR trial T3. (a) $\text{Ce}_2\text{O}_2\text{S}$, (b) Ce_2O_3 . (EDS spectra shown in (c) and (d) correspond to the inclusions shown in (a) and (b), respectively).

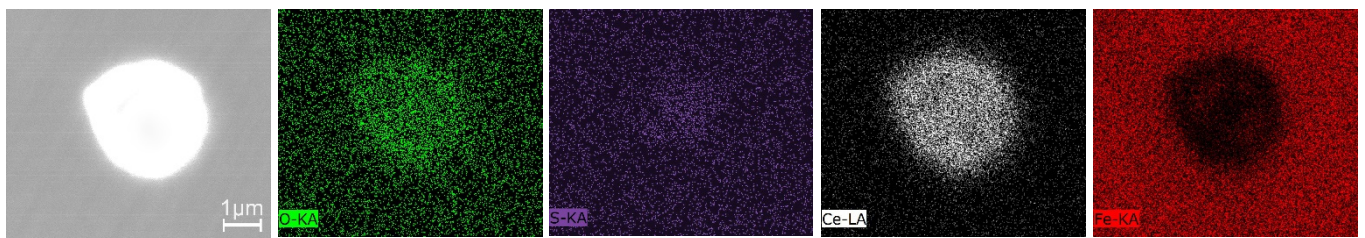


Figure 15. EDS element mappings of $\text{Ce}_2\text{O}_2\text{S}$ inclusion in the liquid metal pool during ESR trial T3.

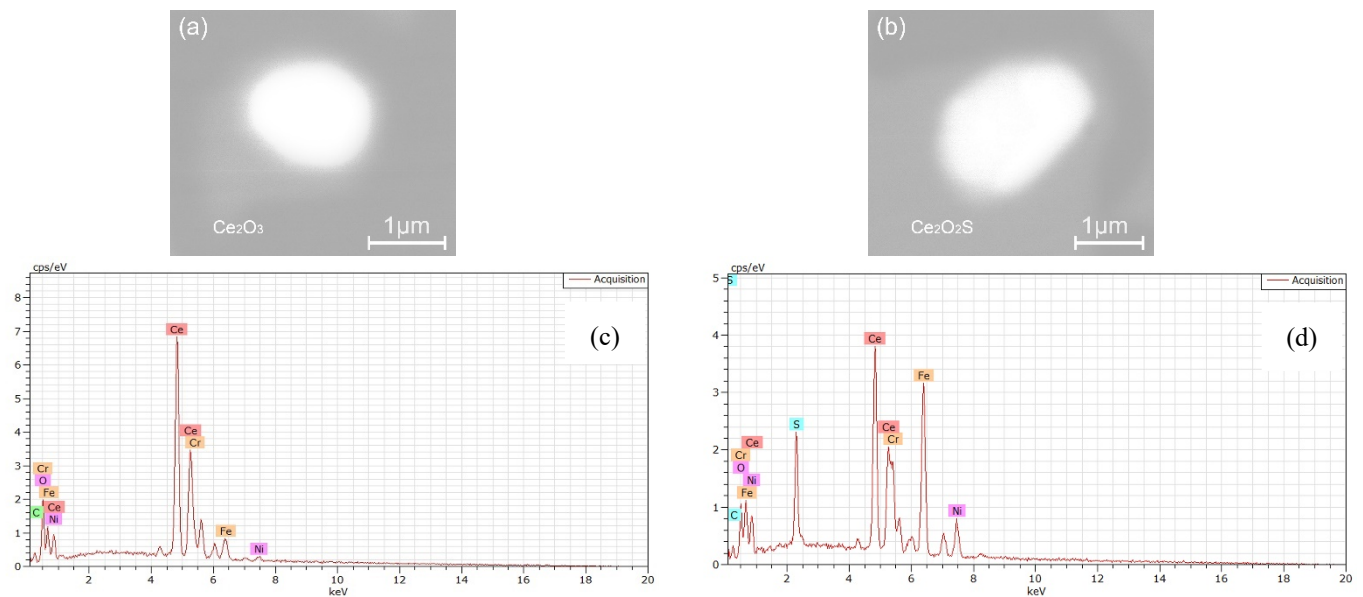


Figure 16. SEM images and EDS spectra of typical inclusions in the ingot C3. (a) Ce_2O_3 , (b) $\text{Ce}_2\text{O}_2\text{S}$. (EDS spectra shown in (c) and (d) correspond to the inclusions shown in (a) and (b), respectively).

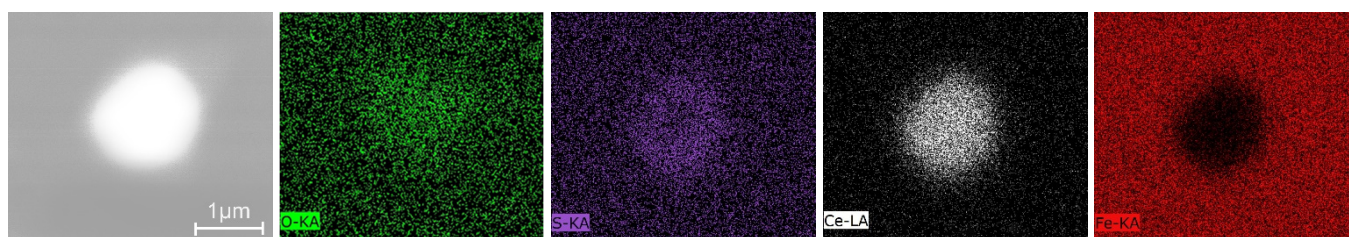


Figure 17. EDS element mappings of $\text{Ce}_2\text{O}_2\text{S}$ inclusion in the ingot C3.

3.4. Size Distribution and Types of Inclusions

Most of inclusions in the Ce-free electrode are 2 to 5 μm in size (accounting for 72% in number proportion), followed by the inclusions larger than 5 μm (21% in the relative fraction), and the number proportion of the inclusion smaller than 2 μm is 7%. The size of inclusions in the electrode with 0.016 mass% Ce is 2 to 5 μm (accounting for 92% in number proportion). The number proportion of inclusions in the size range of 1 μm to 2 μm and the inclusions larger than 5 μm are 6% and 2%, respectively. The proportion of the inclusions in the size range of 1 μm to 2 μm in the electrode with 0.300 mass% Ce is 88%, and the number proportion of inclusions between 2 and 5 μm is 12%.

Figure 18 shows the size distribution of inclusions in liquid metal pools and remelted ingots with different Ce contents. The proportion of inclusions smaller than 2 μm in the liquid metal pool of ESR trial T1 is 67%. The proportion of the number of inclusions occupied between 2 μm and 5 μm is 31%. The size of inclusions smaller than 2 μm in ingot C1 decreased to 34%, and inclusions between 2 and 5 μm increased to 61%. The proportion of the number of inclusions in the size range of 1 μm to 2 μm in the liquid metal pool of the ESR trial T2 is 75%, and the proportion of the number of inclusions occupied between 2 and 5 μm is 25%. The proportion of inclusions in the size range of 1 μm to 2 μm in the remelted ingot decreased to 71%, and the proportion of inclusions in the size range of 2 to 5 μm increased to 27%. The proportion of inclusions larger than 5 μm is 2%. The proportion of inclusions in the liquid pool of the ESR trial T3 remained almost unchanged compared to the remelted ingot C3.

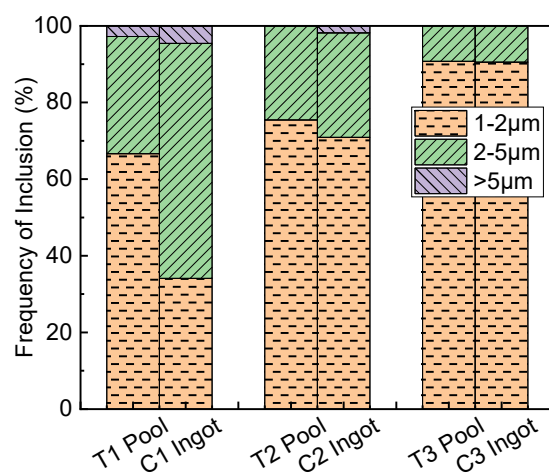


Figure 18. Size distribution of inclusions in the electrode, liquid metal pool, and ingots. (Pool represents liquid metal pool).

Figure 19 shows the distribution of inclusions types in electrodes, liquid metal pools, and remelted ingots with different Ce contents. All inclusions in the Ce-free electrode are identified as $\text{MgO}\cdot\text{Al}_2\text{O}_3$. The type of inclusions in the liquid metal pool of the ESR trial T1 has changed compared to the electrode. The newly formed $\text{CaO}\cdot\text{Al}_2\text{O}_3$ inclusions in the liquid metal pool account for 6% in the number proportion. The proportion of $\text{CaO}\cdot\text{Al}_2\text{O}_3$ inclusions in the ingot account for 49% of the total inclusions.

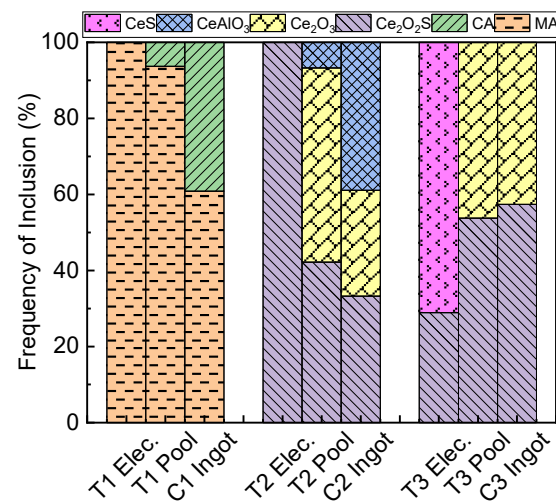


Figure 19. Proportion of different types of inclusion in steel (Elec. and Pool represent electrode and liquid metal pool, respectively. CA and MA represent CaO–Al₂O₃ and MgO·Al₂O₃, respectively).

The rare earth oxide inclusions in the electrode with 0.016 mass% Ce are identified as Ce₂O₂S. The rare earth oxide inclusions present in the liquid metal pool of ESR trial T2 are identified as Ce₂O₃, CeAlO₃, and Ce₂O₂S, accounting for 51%, 7%, and 42% in the number proportion, respectively. The Ce₂O₃ and CeAlO₃ inclusions are newly formed in the liquid metal pool. The proportion of Ce₂O₃ inclusions in the liquid metal pool and ingot reduce from 51% to 28% and CeAlO₃ inclusions increased from 7% to 39%. The Ce₂O₂S inclusions are reduced to 33% in the number proportion after ESR.

The CeS inclusions are completely removed and Ce₂O₃ inclusions are newly formed in the trial T3 during ESR. The proportion of Ce₂O₃ and Ce₂O₂S inclusions in the liquid metal pool is 46% and 54%, respectively. The relative proportions of inclusions in the remelted ingot (43% Ce₂O₃ and 57% Ce₂O₂S) do not change significantly compared to the metal pool.

3.5. Evolution Mechanism of Inclusions during Remelted Remelting

In the present study, thermodynamic calculation is performed for understanding the evolution of inclusions during the ESR with FactSage 8.0 (FSstel, FactPS, and FToxid database). Figures 20 and 21 show the transformation of inclusions precipitation with temperature for electrodes with different Ce content and remelted ingots C1, C2, and C3, respectively.

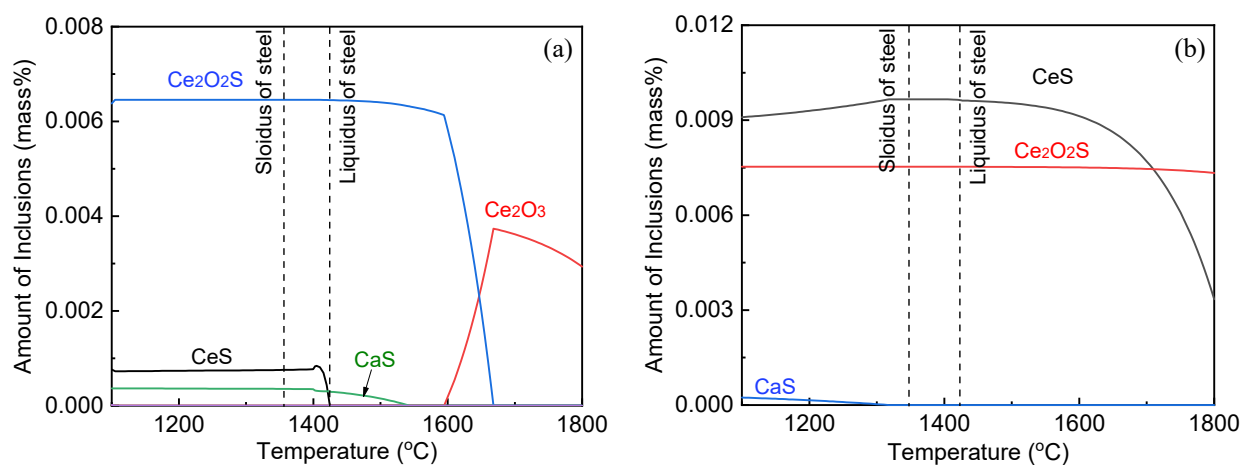


Figure 20. Inclusions formation in the electrode with different Ce contents calculated with FactSage 8.0. (a) 0.016 mass% Ce, (b) 0.300 mass% Ce.

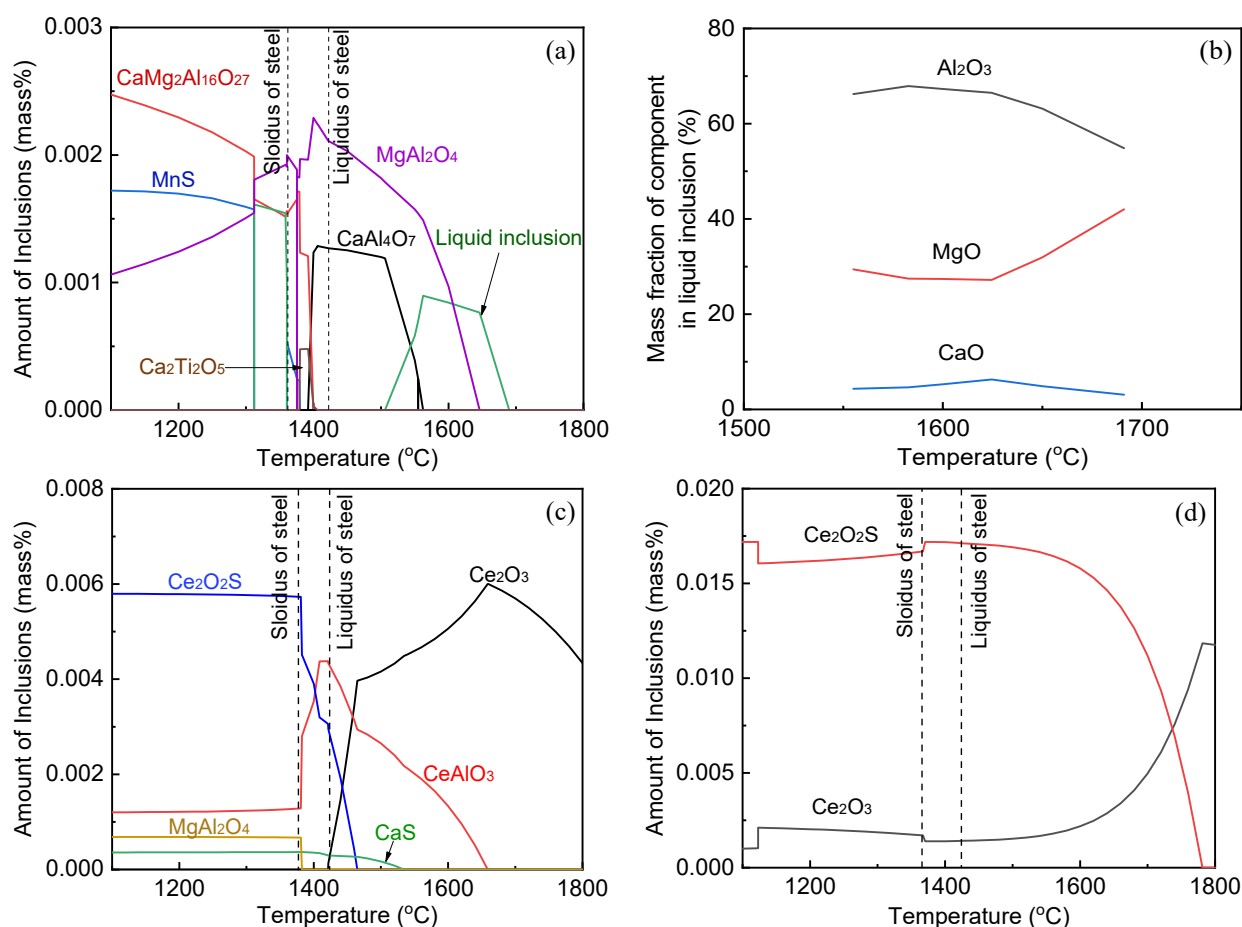


Figure 21. Inclusions transformation in the ingots with different Ce contents calculated with FactSage 8.0. (a) 0 mass% Ce, (c) 0.0055 mass% Ce, (d) 0.063 mass% Ce. (b) The change in the mass fraction of the component in liquid inclusion with 0 Ce.

According to the above experimental observations, no other types of oxide inclusions are observed in the Ce-free electrodes except for MgAl_2O_4 inclusions. The temperature of the liquid metal film steel at the electrode tip is close to the liquidus temperature during ESR [36,37]. The results showed that the part of MgAl_2O_4 inclusions are removed by the adsorption of the molten slag, and the remaining is not removed and entered into the liquid metal pool.

The predicted inclusions transformation with respect to the temperature in the electrodes is present in Figure 20. The Ce_2O_3 inclusions are already formed when the liquid steel temperature at 1800 °C. The Ce_2O_3 inclusions gradually precipitate out as the temperature decrease. when the temperature decreases to 1669 °C, the mass fraction of Ce_2O_3 inclusions decrease sharply, and the mass fraction of $\text{Ce}_2\text{O}_2\text{S}$ inclusions increases sharply. The precipitation rate of $\text{Ce}_2\text{O}_2\text{S}$ inclusions become slow when the temperature of the liquid steel decreases to 1593 °C. According to the thermodynamic calculation, the inclusion in the electrode containing 0.016 mass% Ce is mainly $\text{Ce}_2\text{O}_2\text{S}$, which is consistent with the experimental results.

It suggested that $\text{Ce}_2\text{O}_2\text{S}$ inclusions dissociated into liquid steel as soluble oxygen, sulfur, and cerium as the liquid metal films formed on the downside of the electrode tip and collected into liquid metal droplets subsequently during ESR, whereas the others do not dissociate into liquid steel. Experimental results show that the $\text{Ce}_2\text{O}_2\text{S}$ inclusions are not completely removed. The removal of these $\text{Ce}_2\text{O}_2\text{S}$ inclusions is attributed to the dissociation of a portion of these original oxide inclusions into liquid steel and the absorption of the others by the molten slag phase during the ESR process.

The predicted inclusion transformation with respect to the temperature in the electrode with 0.300 mass% Ce is present in Figure 20b. The amount of the CeS inclusions is higher than that of $\text{Ce}_2\text{O}_3\text{S}$ inclusions. The present thermodynamic calculation supports the above theoretical analysis of oxide inclusions formation and the experimental observations of oxide inclusions in the electrodes.

The electrode tip is heated to near the liquidus temperature of the steel during the ESR. As shown in Figure 20b, CeS and $\text{Ce}_2\text{O}_3\text{S}$ inclusions in the electrode with 0.300 mass% Ce do not dissociate into liquid steel as soluble elements. The experimental results show that CeS inclusions are fully removed by the adsorption of the molten slag before liquid metal droplets collect in the liquid metal pool. According to the results of the experiment, a portion of the $\text{Ce}_2\text{O}_3\text{S}$ inclusions are removed and the remaining enters into the liquid metal pool. The removal of these $\text{Ce}_2\text{O}_3\text{S}$ inclusions is attributed to the absorption of the molten slag during the ESR process.

The predicted inclusions transformation with respect to the temperature in the remelted ingot C1 is present in Figure 21a. The liquid inclusions start to precipitate in the liquid steel at 1690 °C. As the temperature decreases, the mass fraction of liquid inclusions increases sharply. The precipitation rate of liquid inclusions slows down at which point MgAl_2O_4 inclusions begin to precipitate when the temperature is reduced to 1647 °C. When the temperature is reduced to 1574 °C, the mass fraction of liquid inclusions decreases and CaAl_4O_7 inclusions start to precipitate. Figure 21b shows the variation of the mass fraction of each component in the liquid inclusions with temperature. It can be seen from Figure 21b that the liquid inclusions consist of Al_2O_3 , MgO, and CaO, in which Al_2O_3 is dominant in the mass fraction.

As shown in Tables 1 and 2, the reoxidation of liquid steel occurs during the ESR process of trial T1. Thereafter, soluble oxygen reacts with calcium, aluminum and magnesium to form CaAl_4O_7 and MgAl_2O_4 inclusions in the liquid metal pool during the ESR.

All oxide inclusions in the Ce-free electrode were identified as MgAl_2O_4 . The types of inclusions in the liquid metal pool after ESR are MgAl_2O_4 (accounting for 94% in number proportion) and CaAl_4O_7 (6% in number proportion). The proportion of these two types of inclusions in the remelted ingot C1 is 61% and 39%, respectively. Thermodynamic calculations support the above analysis of oxide inclusions in the remelted ingot C1.

The predicted inclusions transformation with respect to the temperature in the ingot C2 is present in Figure 21c. The Ce_2O_3 inclusions already form at 1800 °C in the liquid steel, and Ce_2O_3 inclusions precipitate slowly as the temperature gradually decreases. The mass fraction of Ce_2O_3 inclusions decreases rapidly at 1659 °C, and CeAlO_3 inclusions start to form in the liquid steel.

As listed in Tables 1 and 2, the changes in oxygen content before and after the ESR show that reoxidation of liquid steel occurred in the trial T2 during the ESR. The soluble oxygen inside the liquid metal pool during trial T2 ESR steel reacts with cerium $2[\text{Ce}] + 3[\text{O}] = \text{Ce}_2\text{O}_3(\text{s})$ ($\Delta G^\circ = -1431120 + 121T$ (J/mol)) [38] to form Ce_2O_3 and the Gibbs free energy change of the reaction to -14.56 kJ/mol. Once the soluble oxygen pickup takes place in liquid metal pool (arising from the reoxidation), the soluble oxygen reacts with soluble aluminum and cerium in liquid metal pool to form CeAlO_3 inclusions, $[\text{Ce}] + [\text{Al}] + 3[\text{O}] = \text{CeAlO}_3(\text{s})$ ($\Delta G^\circ = -1366460 + 364T$ (J/mol)) [39] with a Gibbs free energy change of -41.47 kJ/mol. The present thermodynamic calculation supports the above analysis of oxide inclusions formation and the experimental observations of oxide inclusions in the liquid metal pool and ingots.

The predicted inclusions transformation with respect to the temperature in ingot C3 with respect to the temperature is present in Figure 21d. The Ce_2O_3 inclusions are already formed at 1800 °C. When the temperature is reduced to 1781 °C, the mass fraction of Ce_2O_3 inclusions starts to decrease in the liquid steel and the $\text{Ce}_2\text{O}_3\text{S}$ inclusions start to precipitate in the liquid steel.

The change of oxygen content in Tables 1 and 2 shows that reoxidation of liquid steel occurs during ESR. The reoxidation of liquid steel leads to considerable pickup of soluble

oxygen during ESR, which provides a driving force for the generation of Ce_2O_3 inclusions. $2[\text{Ce}] + 3[\text{O}] = \text{Ce}_2\text{O}_3(\text{s})$ ($\Delta G^\circ = -1431120 + 121T$ (J/mol)), the Gibbs free energy change is -142.37 kJ/mol. Soluble oxygen in the liquid metal pool reacts with soluble sulfur and cerium $2[\text{Ce}] + 2[\text{O}] + [\text{S}] = \text{Ce}_2\text{O}_2\text{S}(\text{s})$ ($\Delta G^\circ = -1353590 + 332T$ (J/mol)) [40] to form $\text{Ce}_2\text{O}_2\text{S}$ inclusions. The Gibbs free energy change is -158.85 kJ/mol. According to the experimental results, the $\text{Ce}_2\text{O}_2\text{S}$ inclusions in the electrode cannot be removed completely, the $\text{Ce}_2\text{O}_2\text{S}$ inclusions in the liquid metal pool originate from reoxidation inside the liquid metal pool and the original inclusions that has not been removed. The thermodynamic calculations results are consistent with the experimental observations and analysis of the formation of oxide inclusions in the liquid metal pool and remelted ingot.

The liquid steel solidification progresses in a non-equilibrium state during the ESR practice, which leads to insufficient solute diffusion in solid [41,42]. The evolution of inclusions during the solidification of liquid steel with different Ce contents is calculated using the non-equilibrium module (Scheil-Gulliver model) of the thermodynamic software FactSage 8.0.

As shown in Figure 22a, MgAl_2O_4 and CaAl_4O_7 inclusions are formed at the high-temperature stage (around 1600°C). The mass fraction of oxide inclusions forms at temperatures below the liquidus temperature of the steel is virtually nothing during the solidification process. Figure 22b shows that the Ce_2O_3 inclusions already formed at 1600°C in the liquid steel. The mass fraction of Ce_2O_3 inclusions no longer changes as the temperature decreases. When the temperature reaches to 1600°C , CeAlO_3 inclusions are formed in liquid steel and the mass fraction of oxide inclusions does not change when the temperature is reduced to 1449°C . At the temperature below the liquidus temperature of the steel, the mass fraction of oxide inclusions does not change. As shown in Figure 22c, the Ce_2O_3 and $\text{Ce}_2\text{O}_2\text{S}$ inclusions are formed at 1600°C in liquid steel. As the temperature of liquid steel decreases, the mass fraction of Ce_2O_3 and $\text{Ce}_2\text{O}_2\text{S}$ inclusions no longer change.

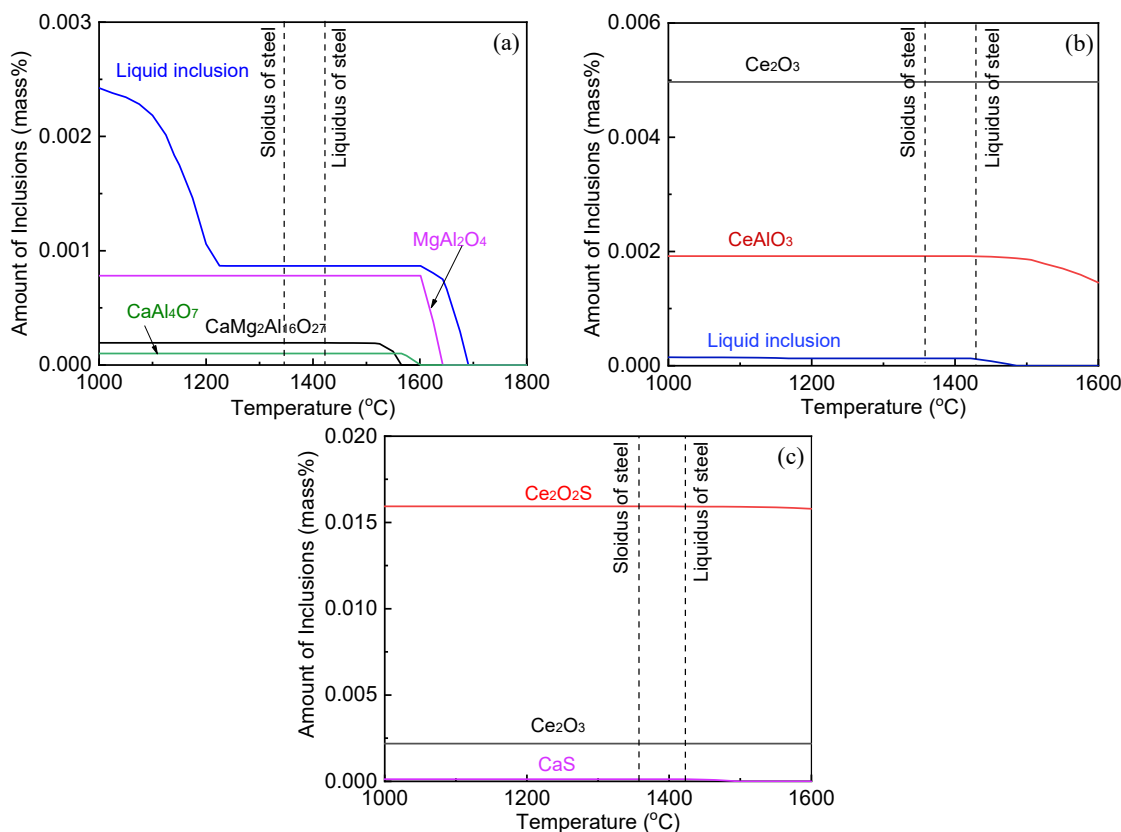


Figure 22. (a) Non-equilibrium precipitation of inclusions during the cooling and solidification of liquid steel. (a) 0 mass% Ce, (b) 0.0055 mass% Ce, (c) 0.063 mass% Ce.

As shown in Figure 22, amount of individual type of oxide inclusions does not change during liquid steel solidification. It can be learned that no fresh oxide inclusions are generated during the solidification of liquid steel. The types of inclusions in the liquid metal pools of the ESR trials T1, T2, and T3 are the same as those in the remelted ingots. This is consistent with the experimental observations. The differences in the number proportions of different types of inclusions between liquid metal pool and remelted ingot are attributed to the removal through floatation before full solidification of liquid steel during the ESR.

4. Conclusions

1. The Al pickup in the steel is caused by the Al addition for deoxidation during the ESR process, rather than the reduction of Al_2O_3 in the slag by Ce. The soluble oxygen pickup is generated in liquid steel due to the decomposition of FeO in the slag and desulfurization during the protective argon gas atmosphere ESR.
2. The oxide inclusions in Ce-free electrode are $\text{MgO}\cdot\text{Al}_2\text{O}_3$, part of which are removed by molten slag absorption during the ESR. The oxide inclusions in liquid metal pool are mainly $\text{MgO}\cdot\text{Al}_2\text{O}_3$ and $\text{CaO}\cdot\text{Al}_2\text{O}_3$ (6% in number fraction). The soluble oxygen that arising from reoxidation of liquid steel during the ESR react with soluble calcium and aluminum to form $\text{CaO}\cdot\text{Al}_2\text{O}_3$ inclusions. $\text{MgO}\cdot\text{Al}_2\text{O}_3$ inclusions are originated from reoxidation products and the relics from the electrode.
3. The oxide inclusions in the electrode with 0.016 mass% Ce are $\text{Ce}_2\text{O}_2\text{S}$. Part of $\text{Ce}_2\text{O}_2\text{S}$ inclusions are removed during ESR in two ways: (I) dissociated into soluble oxygen and soluble elements in liquid steel, (II) absorbed by molten slag. The oxide inclusions in the liquid metal pool are Ce_2O_3 , CeAlO_3 , and $\text{Ce}_2\text{O}_2\text{S}$. CeAlO_3 inclusions are reoxidation product, and $\text{Ce}_2\text{O}_2\text{S}$ inclusions are the relics from the electrode. The proportions of Ce_2O_3 , CeAlO_3 and $\text{Ce}_2\text{O}_2\text{S}$ inclusions in ingot are 28%, 39%, and 33%, respectively.
4. The rare-earth inclusions in the electrode with 0.300 mass% Ce are $\text{Ce}_2\text{O}_2\text{S}$ and CeS. The CeS inclusions are fully removed during ESR. Part of $\text{Ce}_2\text{O}_2\text{S}$ inclusions are removed by slag adsorption. The oxide inclusions in liquid metal pool are Ce_2O_3 (reoxidation products, 46% in number proportion) and $\text{Ce}_2\text{O}_2\text{S}$ (54% in number fraction). $\text{Ce}_2\text{O}_2\text{S}$ inclusions in liquid metal pool are originated from the relics of electrode and reoxidation products. The proportion of Ce_2O_3 and $\text{Ce}_2\text{O}_2\text{S}$ inclusions in remelted ingots are 43% and 57%, respectively.
5. No fresh oxide inclusions are generated during the solidification of liquid steel. The differences in the number proportions of different types of inclusions between liquid metal pool and remelted ingot are attributed to the removal through floatation before full solidification of liquid steel during the ESR.

Author Contributions: Conceptualization, C.S.; methodology, Z.W. and X.Z.; formal analysis, Z.W. and C.S.; investigation, Z.W. and C.S.; writing—original draft preparation, Z.W., S.W. and C.S.; writing—review and editing, C.S. and X.Z.; supervision, C.S. and J.L.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant Nos. 52074027 and 51874026).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express appreciation to the National Natural Science Foundation of China for the financial support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kondrat'Ev, S.Y.; Kraposhin, V.S.; Anastasiadi, G.P.; Talis, A.L. Experimental observation and crystallographic description of M_7C_3 carbide transformation in Fe–Cr–Ni–C HP type alloy. *Acta Mater.* **2015**, *100*, 275–281. [\[CrossRef\]](#)
2. Hedaia, F.; Dehmolaie, R.; Khorasani, M.; Lotfi, B. Long-term oxidation behaviour and thermal stability of heat-resistant stainless steel claddings deposited on AISI 316 stainless steel by the GTAW process. *Surf. Coat. Technol.* **2021**, *424*, 127605. [\[CrossRef\]](#)
3. Mazánová, V.; Heczko, M.; Polák, J. Fatigue crack initiation and growth in 43Fe-25Ni-22.5Cr austenitic steel at a temperature of 700 °C. *Int. J. Fatigue* **2018**, *114*, 11–21. [\[CrossRef\]](#)
4. Guo, H.; Yang, S.F.; Wang, T.T.; Yuan, H.; Zhang, Y.L.; Li, J.S. Microstructure evolution and acicular ferrite nucleation in inclusion-engineered steel with modified MgO@C nanoparticle addition. *J. Mater. Sci. Technol.* **2022**, *99*, 277–287. [\[CrossRef\]](#)
5. Xu, X.; Benaarbia, A.; Allen, D.J.; Jepson, M.A.E.; Sun, W. Investigation of microstructural evolution and creep rupture behaviour of 9% Cr MarBN steel welds. *Mater. Sci. Eng. A* **2020**, *791*, 139546. [\[CrossRef\]](#)
6. Yang, Z.; Zhang, J.; Li, S.; Li, G.; Wang, Q.; Hui, W.; Weng, Y. On the critical inclusion size of high strength steels under ultra-high cycle fatigue. *Mater. Sci. Eng. A* **2006**, *427*, 167–174. [\[CrossRef\]](#)
7. Meurling, F.; Melander, A.; Tidesten, M.; Westin, L. Influence of carbide and inclusion contents on the fatigue properties of high speed steels and tool steels. *Int. J. Fatigue* **2001**, *23*, 215–224. [\[CrossRef\]](#)
8. Shibaeva, T.V.; Laurinavichyute, V.K.; Tsirlina, G.A.; Arsenkin, A.M.; Grigorovich, K.V. The effect of microstructure and non-metallic inclusions on corrosion behavior of low carbon steel in chloride containing solutions. *Corros. Sci.* **2014**, *80*, 299–308. [\[CrossRef\]](#)
9. Tomita, Y. Effect of morphology of nonmetallic inclusions on tensile properties of quenched and tempered 0.4C-Cr-Mo-Ni steel. *Mater. Charact.* **1995**, *34*, 121–128. [\[CrossRef\]](#)
10. Garrison, W.M.; Wojcieszynski, A.L. A discussion of the effect of inclusion volume fraction on the toughness of steel. *Mater. Sci. Eng. A* **2007**, *464*, 321–329. [\[CrossRef\]](#)
11. Shi, C.B.; Wang, S.J.; Li, J.; Cho, J.W. Non-metallic inclusions in electrosag remelting: A review. *J. Iron Steel. Res. Int.* **2021**, *28*, 1483–1503. [\[CrossRef\]](#)
12. Wang, M.J.; Mu, S.M.; Sun, F.F.; Wang, Y. Influence of rare earth elements on microstructure and mechanical properties of cast high-speed steel rolls. *J. Rare Earths* **2007**, *25*, 490–494. [\[CrossRef\]](#)
13. Chen, R.C.; Wang, Z.G.; He, J.G.; Zhu, F.S.; Li, C.H. Effects of rare earth elements on microstructure and mechanical properties of H13 die steel. *Metals* **2020**, *10*, 918. [\[CrossRef\]](#)
14. Wang, L.M.; Du, X.J.; Gan, Y.; Liu, L.; Ye, X.N.; Jiang, L.Z. Effect of rare earths on oxidation resistance of heat resistant steel. *J. Rare Earths* **2010**, *28*, 489–491. [\[CrossRef\]](#)
15. Gao, J.Z.; Fu, P.X.; Liu, H.W.; Li, D.Z. Effects of rare earth on the microstructure and impact toughness of H13 Steel. *Metals* **2015**, *5*, 383–394. [\[CrossRef\]](#)
16. Zhang, S.C.; Yu, J.T.; Li, H.B.; Jiang, Z.H.; Geng, Y.F.; Feng, H.; Zhang, B.B.; Zhu, H.C. Refinement mechanism of cerium addition on solidification structure and sigma phase of super austenitic stainless steel S32654. *J. Mater. Sci. Technol.* **2022**, *102*, 105–114. [\[CrossRef\]](#)
17. Xu, Y.W.; Song, S.; Wang, J.W. Effect of rare earth cerium on the creep properties of modified 9Cr–1Mo heat-resistant steel. *Mater. Lett.* **2015**, *161*, 616–619. [\[CrossRef\]](#)
18. Wang, H.P.; Xiong, L.; Zhang, L.; Wang, Y.; Shu, Y.Y.; Zhou, Y. Investigation of RE–O–S–As inclusions in high carbon steels. *Metall. Mater. Trans. B* **2017**, *48*, 2849–2858. [\[CrossRef\]](#)
19. Liu, Y.Y.; Bao, X.R.; Chen, L.; Jin, Z.L.; Ren, H.P. Rare Earth microalloyed elements' influence on the organization and capability of X65 pipeline steel. *J. Rare Earths* **2010**, *28*, 497–500. [\[CrossRef\]](#)
20. Chen, L.; Ma, X.C.; Wang, L.M.; Ye, X.N. Effect of rare earth element yttrium addition on microstructures and properties of a 21Cr–11Ni austenitic heat-resistant stainless steel. *Mater. Des.* **2011**, *32*, 2206–2212. [\[CrossRef\]](#)
21. Zhao, Y.Y.; Wang, J.F.; Zhou, S.; Wang, X.D. Effects of rare earth addition on microstructure and mechanical properties of a Fe–15Mn–1.5Al–0.6C TWIP steel. *Mater. Sci. Eng. A* **2014**, *608*, 106–113. [\[CrossRef\]](#)
22. Wang, Y.G.; Liu, C.J. Agglomeration characteristics of various inclusions in Al-killed molten steel containing rare earth element. *Metall. Mater. Trans. B* **2020**, *51*, 2585–2595. [\[CrossRef\]](#)
23. Huang, Y.; Cheng, G.G.; Li, S.J.; Dai, W.X. Effect of cerium on the behavior of inclusions in H13 steel. *Steel Res. Int.* **2018**, *89*, 1800371. [\[CrossRef\]](#)
24. Liu, H.H.; Fu, P.X.; Liu, H.W.; Cao, Y.F.; Sun, C.; Du, N.Y.; Li, D.Z. Effects of rare earth elements on microstructure evolution and mechanical properties of 718H pre-hardened mold steel. *J. Mater. Sci. Technol.* **2020**, *50*, 245–256. [\[CrossRef\]](#)
25. Feng, H.; Lu, P.C.; Li, H.B.; Jiang, Z.H. Effect of Mg pretreatment and Ce addition on cleanliness and inclusion evolution in high-nitrogen stainless bearing steels. *Metall. Mater. Trans. B* **2022**, *53*, 864–876. [\[CrossRef\]](#)
26. Geng, R.M.; Li, J.; Shi, C.B. Effect of Ce on inclusion evolution and HAZ mechanical properties of Al-killed high-strength steel. *Ironmak. Steelmak.* **2021**, *48*, 796–802. [\[CrossRef\]](#)
27. Geng, R.M.; Li, J.; Shi, C.B. Evolution of inclusions with Ce addition and Ca treatment in Al-killed steel during RH refining process. *ISIJ Int.* **2021**, *61*, 1506–1513. [\[CrossRef\]](#)

28. Shi, C.B.; Yu, W.T.; Wang, H.; Li, J.; Jiang, M. Simultaneous modification of alumina and $\text{MgO} \cdot \text{Al}_2\text{O}_3$ inclusions by calcium treatment during electroslag remelting of stainless tool steel. *Metall. Mater. Trans. B* **2016**, *48*, 146–161. [[CrossRef](#)]
29. Li, X.; Jiang, Z.H.; Geng, X.; Chen, M.J.; Cui, S. Effect of rare earth–magnesium alloy on inclusion evolution in industrial production of die steel. *Steel Res. Int.* **2019**, *90*, 1900103. [[CrossRef](#)]
30. Shi, C.B.; Zheng, D.L.; Guo, B.S.; Li, J.; Jiang, F. Evolution of oxide–sulfide complex inclusions and its correlation with steel cleanliness during electroslag rapid remelting (ESRR) of tool steel. *Metall. Mater. Trans. B* **2018**, *49*, 3390–3402. [[CrossRef](#)]
31. Wang, S.J.; Shi, C.B.; Liang, Y.J.; Wan, X.X.; Zhu, X. Evolution and formation of non-metallic inclusions during electroslag remelting of a heat-resistant steel for ultra-supercritical power plants. *Metall. Mater. Trans. B* **2022**, *53*, 3095–3114. [[CrossRef](#)]
32. Gao, S.; Wang, M.; Guo, J.L.; Wang, H.; Zhi, J.G.; Bao, Y.P. Characterization transformation of inclusions using rare earth Ce treatment on Al-Killed titanium alloyed interstitial free steel. *Steel Res. Int.* **2019**, *90*, 1900194. [[CrossRef](#)]
33. Geng, R.M.; Li, J.; Shi, C.B.; Zhi, J.G.; Lu, B. Effect of Ce-La on inclusion evolution in Al-killed high strength steel. *Metall. Res. Technol.* **2020**, *117*, 616. [[CrossRef](#)]
34. Shi, C.B.; Wang, H.; Li, J. Effects of reoxidation of liquid steel and slag composition on the chemistry evolution of inclusions during electroslag remelting. *Metall. Mater. Trans. B* **2018**, *49*, 1675–1689. [[CrossRef](#)]
35. Shi, C.B. Deoxidation of electroslag remelting (ESR)—A review. *ISIJ Int.* **2020**, *60*, 1083–1096. [[CrossRef](#)]
36. Liu, H.L.; Liu, C.J.; Jiang, M.F. Effect of rare earths on impact toughness of a low-carbon steel. *Mater. Des.* **2012**, *33*, 306–312. [[CrossRef](#)]
37. Kruger, D.; Garbers, C.A. Characteristics and modification of non-metallic inclusions in titanium-stabilized aisi 409 ferritic stainless steel. *Metall. Mater. Trans. B* **2017**, *48*, 1514–1532. [[CrossRef](#)]
38. Wen, T.J.; Ren, Q.; Zhang, L.F.; Wang, J.J.; Ren, Y.; Zhang, J.; Yang, W.; Xu, A.J. Evolution of nonmetallic inclusions during the electroslag remelting process. *Steel Res. Int.* **2021**, *92*, 2000629. [[CrossRef](#)]
39. Ren, Q.; Zhang, L.F. Effect of cerium content on inclusions in an ultra-low-carbon aluminum-killed steel. *Metall. Mater. Trans. B* **2020**, *51*, 589–600. [[CrossRef](#)]
40. Adabavazeh, Z.; Hwang, W.S.; Su, Y.H. Effect of adding cerium on microstructure and morphology of Ce-based inclusions formed in low-carbon steel. *Sci. Rep.* **2017**, *7*, 46503. [[CrossRef](#)]
41. Shi, C.B.; Zheng, X.; Yang, Z.B.; Lan, P.; Li, J.; Jiang, F. Effect of melting rate of electroslag rapid remelting (ESRR) on the microstructure and carbides in a hot work tool steel. *Metals Mater. Int.* **2021**, *27*, 3603–3616. [[CrossRef](#)]
42. Klancnik, U.; Kosec, B.; Mrvar, P.; Medved, J. Non-equilibrium solidification and microsegregation in centrifugally cast high speed steel for rolls. *J. Min. Metall. B* **2018**, *54*, 59–66. [[CrossRef](#)]