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Evolution of Nonmetallic Inclusion during Steelmaking Process of Cold Heading Steel SWRCH35K

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Abstract

In order to analyze the evolution of the inclusions in the cold heading steel SWRCH35K during the steelmaking process, a systematic sampling of the steelmaking processes in a steel plant was carried out. Both SEM-EDS and the image processing software Image-Pro-Plus6.0 were employed to analyze the chemical composition, morphology, quantity and size of non-metal inclusions in the steel samples. The results show that from BOF tapping to continuous casting tundish, the composition of inclusions in SWRCH35K steel changes from Al_2O_3 → $MgO{\cdot}Al_2O_3$ → CaO-MgO-Al_2O_3-CaS, and the typical morphology of the inclusions in the steel gradually changes from irregular blocks and clusters to spherical. The number of inclusions in the BOF argon blowing station is the largest, 213#/mm^2, while the number of inclusions at the end of LF refining is the least, about 12#/mm^2, and there are basically no inclusions above 5 μm. In addition, LF calcium treatment will adversely affect the size and quantity control of inclusions in steel. In order to effectively reduce the large-size calcium-containing spherical oxide inclusions in cold heading steel, it is necessary to find a technical method that can replace LF calcium treatment to solve the problem of molten steel continuous casting.

Keywords

Cold Heading Steel, Inclusions, LF Refining, Calcium Treatment

1. Introduction

SWRCH35K is a medium carbon cold heading steel, which is generally used to manufacture standard fasteners of class 8.8, such as bolts and screws, and it is widely used in machinery manufacturing, engineering construction, automobile and household appliances and other fields [1] [2] [3]. In the process of forming standard fasteners for cold heading processing, the cold heading steel needs to bear a great amount of deformation and deformation speed, so it is required to have good plasticity and low work hardening rate [4] [5]. Non-metallic inclusions in steel destroy the continuity of steel matrix, seriously affect the plasticity and work hardening rate of steel, and cause cracking of steel during cold heading, which needs to be paid attention to and controlled in steelmaking process. Aluminum deoxidation is generally adopted in SWRCH35K steelmaking process, not only because Al-killed process can obtain lower oxygen content and higher cleanliness, but also because the austenite grain size of cold heading steel can be obviously refined by adding proper amount of aluminum. In order to improve the castability of continuous casting, inclusions need to be removed and modified in LF refining process, and calcium treatment is still an effective means to modify inclusions so far [6] [7] [8]. Lu [9] *et al.* found that the LF refining process can effectively modify the Al_2O_3 inclusion in the cold heading steel by refining with high basicity and strong reducing slag combined with calcium treatment, thus improving the castability and cold heading performance of the steel. Zhao [10] *et al.* found that in industrial tests, if sulfur content in molten steel is high or calcium is fed too much, a large number of CaS inclusions will be generated, which is not conducive to the castability of molten steel and the control of inclusions in steel. In this paper, by sampling each process of the cold heading steel SWRCH35K produced by a steel plant, the formation and evolution of inclusions in the steelmaking process were studied by means of SEM-EDS and Image-Pro-Plus, so as to provide reference and guidance for the subsequent optimization of steelmaking process.

2. Materials and Experimental Method

2.1. Materials

The test material was SWRCH35K cold heading steel, and the steelmaking production process was hot metal desulfurization → basic oxygen furnace(BOF) primary smelting → ladle furnace (LF) secondary refining → calcium treatment → soft blowing → billet continuous casting. Aluminum was added to deoxidize the steel in the tapping process of the converter, high basicity slag was produced in the LF refining process to refine the molten steel, and calcium was fed after the refining. In order to ensure sufficient deoxidation and desulfurization of molten steel, combined with industrial production big data, the basicity $R(w(CaO)/w(SiO_2))$ of refining slag was controlled at 5.0 - 6.8, and the soft blowing time after calcium treatment was greater than or equal to 10 min. **Table 1** shows the chemical composition of the SWRCH35K cold heading steel. **Table 2** presents the chemical composition of the LF refining slag for SWRCH35K cold heading steel, which was measured by X-ray fluorescence spectroscopy.

Table 1. Chemical composition of SWRCH35K cold heading steel %.

C	Si	Mn	P	S	Alt	Ca
0.34	0.14	0.83	0.0112	0.006	0.03	0.0015

Table 2. Chemical composition of LF refining slag for SWRCH35K %.

FeO	CaO	Al_2O_3	SiO_2	MgO	MnO
0.54	57.98	22.16	9.98	3.96	0.10

In order to systematically study the evolution behavior of inclusions in the whole smelting process of SWRCH35K, steel samples (numbered 1 - 5) were taken from ladle during the end of converter tapping, LF entering, LF ending and after calcium treatment and the continuous casting tundish respectively. The sampling flow diagram of the whole smelting process is shown in **Figure 1**.

2.2. Sample Processing and Testing Method

The steel samples were processed into 10 mm × 10 mm × 10 mm metallography samples. After coarse grinding, fine grinding and polishing, the morphology and composition of inclusions in the steel were detected by SEM-EDS, and 50 fields of view were detected for each sample. With the help of Image-Pro-Plus6.0 software, the number and size of inclusions were measured.

3. Results

3.1. Composition and Typical Morphology of Inclusions in Each Process

After the steel samples taken in each smelting process were processed and prepared, the electron microscope scanning was carried out, and the EDS detection was carried out on the inclusions to obtain the content of each element of the inclusions, which was converted into the mass percentage of the corresponding compound according to the conservation of metal elements, and the average composition of oxide inclusions in each process was counted, as shown in **Figure 2**. The typical inclusion morphology in the steel samples of each process was shown in **Figure 3**, and the EDS detection results of non-metallic inclusion in **Figure 3** are presented in **Table 3**. In the argon blowing station after BOF tapping and LF entering stage, the main components of inclusions in steel were Al_2O_3 system inclusions, and its morphology was mainly irregular block, distributed in clusters with large size. After LF refining, the composition of inclusions changed obviously, the proportion of $MgO \cdot Al_2O_3$ spinel inclusions was the highest, and there was also a small amount of $CaO\text{-}MgO\text{-}Al_2O_3\text{-}CaS$ composite inclusions. High melting temperature $MgO \cdot Al_2O_3$ spinel inclusions were regular blocks, while $CaO\text{-}MgO\text{-}Al_2O_3\text{-}CaS$ composite inclusions tended to be spherical, which indirectly indicated that the melting point of these calcium containing inclusions was lower than the temperature of molten steel. With the progress of calcium treatment of molten steel, the MgO content in the inclusions decreased, and the main inclusions became CaO-MgO-Al_2O_3-CaS, and there were local inclusions rich in CaS. From LF soft blowing to tundish, the composition of inclusions had little change, and the morphology also presented spherical morphology.

3.2. Quantity Density Change of Inclusions in Each Process

The number and size distribution of inclusions were counted by Image-Pro-Plus 6.0 Image processing software. In order to reduce the pollution influence of polishing powder during sample preparation, inclusions with a statistical size of more than 3 μm were selected. The number and size changes of inclusions in the samples taken from each process of cold heading steel SWRCH35K steelmaking are shown in Figure 4. During the tapping process of the BOF, aluminum was

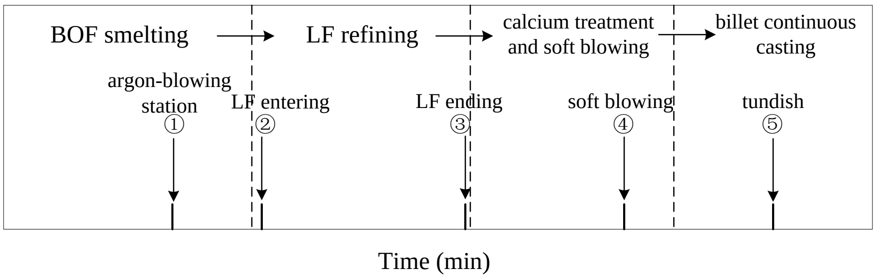

Figure 1. Sampling flow chart during the melting process.

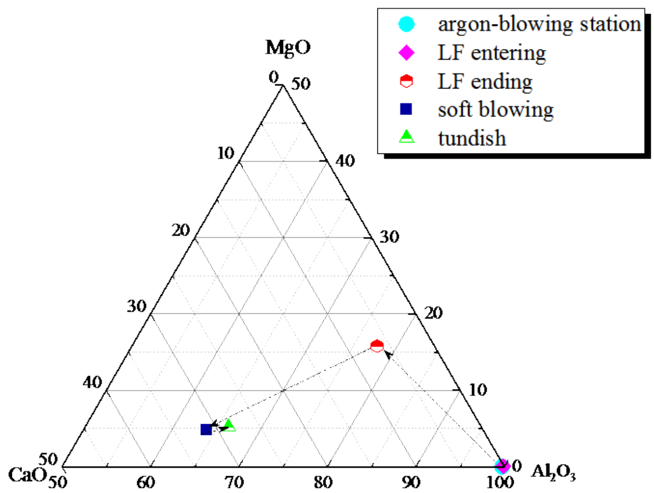

Figure 2. Evolution of average composition of non-metallic inclusions during the process.

Table 3. EDS detection results of non-metallic inclusion in Figure 3, wt%.

Number	Al	Ca	Si	Mg	S	Mn
1	25.2	—	—	—	1.0	0.7
2	35.2	1.2	—	—	—	—
3	10.1	1.9	—	3.5	0.4	—
4	8.1	9.2	0.2	0.6	3.2	0.4
5	3.8	6.4	—	0.7	3.8	—

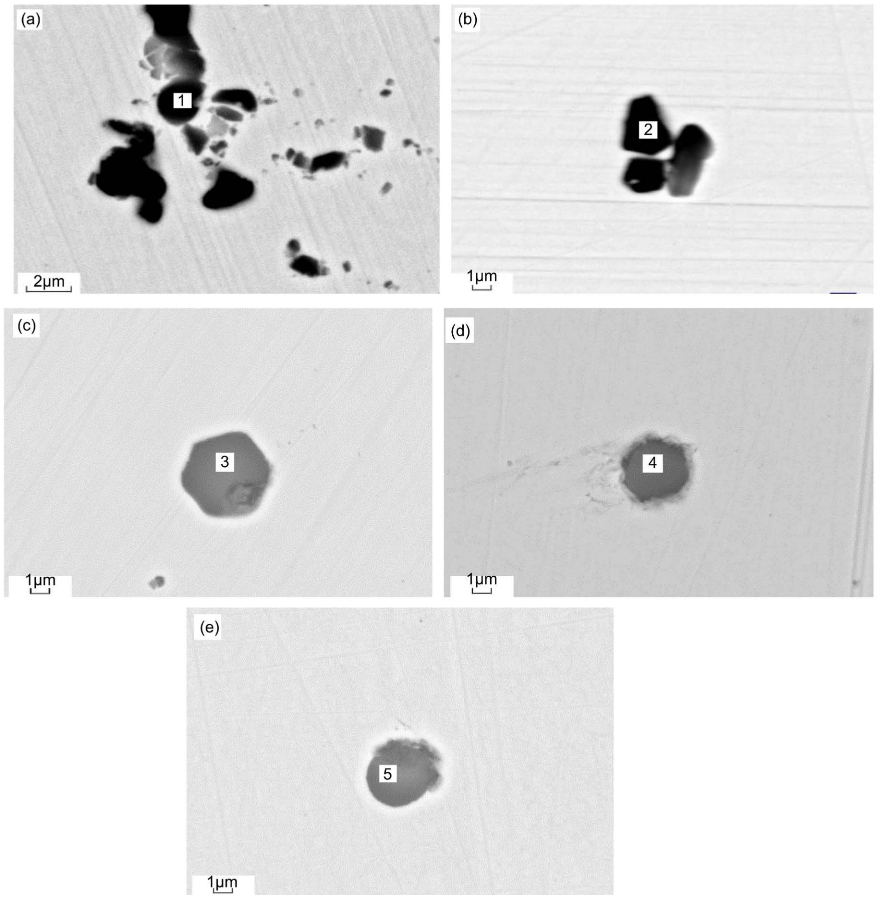

Figure 3. Typical morphological characteristics of inclusions in each process. (a) Argon-blowing station; (b) LF entering; (c) LF ending; (d) Calcium treatment; (e) Tundish.

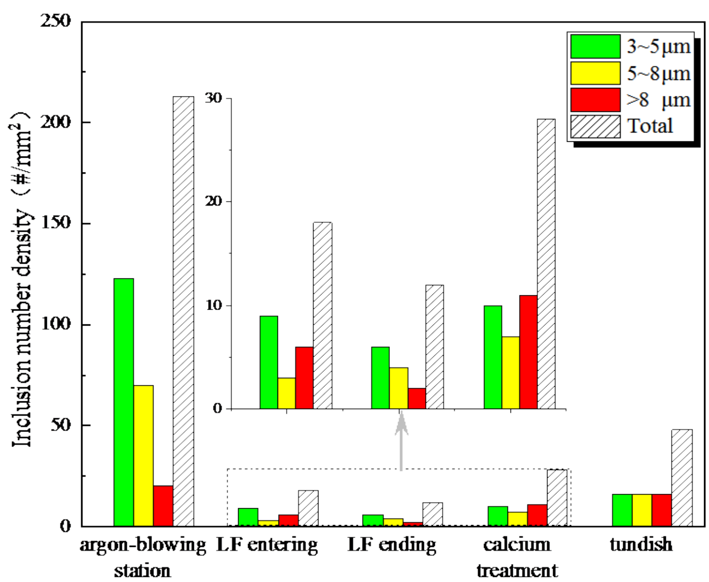

Figure 4. Changes in the number and size of inclusions in each process.

added to deoxidize the molten steel. The aluminum reacted with the dissolved oxygen in the steel to form a large number of deoxidized products. At this time, the number of inclusions was the largest, 213#/mm^2, and the size of inclusions was large, many of which were more than 8 μm. With the argon blowing treatment of molten steel, a large number of deoxidized products floated up to remove, and the number of inclusions in steel decreased sharply, and the number of inclusions decreased to 18#/mm^2 in the process of LF entering. During LF refining, the number of inclusions continued to decrease. At the LF ending, the number of inclusions was about 12#/mm^2, and the large inclusions above 5 μm were almost completely removed. After calcium treatment, the number of inclusions increased to 28#/mm^2, and the size increased. In the tundish, the number of inclusions in the steel increased to 48#/mm^2, and the number of large inclusions above 8 μm increased, which was related to the secondary oxidation of molten steel caused by improper casting protection.

3.3. Discussion

In the BOF tapping process of SWRCH35K, aluminum is added for precipitation deoxidation. The added aluminum reacts violently with the dissolved oxygen in the molten steel, a lot of Al_2O_3 clusters are formed quickly, and most of them float into slag while a small amount of them remains in liquid steel with very low dissolved oxygen content. The reaction equation is shown in formula (1). From the argon blowing station to the LF entering, the inclusions in the steel are mainly Al_2O_3 system inclusions. As the LF refining proceeds, the acid soluble aluminum in the steel is further increased by adding aluminum particles or aluminum wires. At this time, the MgO in the refining slag and ladle refractory will be reduced by aluminum to [Mg] and enter the molten steel, as shown in formula (2), and then the reaction of formula (3) will occur to produce a large amount of $MgO \cdot Al_2O_3$ spinel inclusions. After calcium treatment, Al_2O_3 inclusions and $MgO \cdot Al_2O_3$ spinel inclusions in the steel are modified. The reaction equations are shown in formulas (4) and (5). From the BOF tapping to the LF calcium treatment stage, the inclusions in the steel undergo a transition from Al_2O_3 → $MgO \cdot Al_2O_3$ → $CaO \cdot MgO \cdot Al_2O_3$ [11]. In addition, excessive [Ca] after calcium treatment will react with [S] in steel in formula (6) during solidification of molten steel, and generally precipitate around oxide inclusions.

Deoxidation reaction during BOF tapping process:

$$2\mathrm{Al} + 3[\mathrm{O}] = \mathrm{Al_2O_3} \tag{1}$$

MgO in refractory and slag is reduced:

$$2[\mathrm{Al}] + 3\mathrm{MgO}(\mathrm{s}) = \mathrm{Al_2O_3} + 3[\mathrm{Mg}] \tag{2}$$

Formation of spinel inclusions in molten steel:

$$\mathrm{Al_2O_3} + [\mathrm{Mg}] + [\mathrm{O}] = \mathrm{MgO} \cdot \mathrm{Al_2O_3}(\mathrm{s}) \tag{3}$$

Modification of alumina and spinel inclusions in molten steel by calcium treatment:

$$x[\mathrm{Ca}] + (y + x/3)\mathrm{Al_2O_3} = x\mathrm{CaO} \cdot y\mathrm{Al_2O_3} + 2x/3[\mathrm{Al}] \tag{4}$$

$$x[\mathrm{Ca}] + y\mathrm{MgO} \cdot z\mathrm{Al_2O_3}(\mathrm{s}) = x\mathrm{CaO} \cdot (y - x)\mathrm{MgO} \cdot z\mathrm{Al_2O_3} + x[\mathrm{Mg}] \quad (5)$$

Excess calcium forms calcium sulfide inclusions:

$$[\mathrm{Ca}] + [\mathrm{S}] = \mathrm{CaS}(\mathrm{s}) \quad (6)$$

Calcium treatment for molten steel can effectively modify the composition of inclusions in the steel, prevent the adhesion and aggregation of inclusions in the steel on the inner wall of the continuous casting nozzle, and thus improve the castability of molten steel for continuous casting, but it will bring adverse effects on the size and quantity control of inclusions in the steel. Because by increasing the Ca amount in inclusions, their equivalent circle diameters grew, and their aspect ratios went toward unity [12]. The lower the calcium content in molten steel, the smaller the average size of inclusions in steel. The large size low-melting point inclusions formed after calcium treatment have a small contact angle with liquid steel and argon bubble, and these inclusions are difficult to be removed by bottom-blowing argon floating up [13]. These large size spherical inclusions containing calcium remaining in steel often have adverse effects on the performance of cold heading steel products. Other alternative techniques need to be investigated to continuously improve the inclusion control level of cold heading steel.

4. Conclusions

1) The composition of inclusions in SWRCH35K cold heading steel changes from Al_2O_3 → $MgO \cdot Al_2O_3$ → CaO-MgO-Al_2O_3-CaS from BOF tapping to continuous casting tundish, and the typical morphology of the inclusions in the steel gradually changes from irregular blocks and clusters to spherical.

2) For the whole steelmaking process of cold heading steel SWRCH35K, the number of inclusions in the BOF argon blowing station is the largest, 213#/mm^2, while the number of inclusions at the end of LF refining is the least, about 12#/mm^2, and there are basically no inclusions above 5 μm. LF calcium treatment and secondary oxidation of continuous casting lead to the increase of the number and size of oxide inclusions in steel.

3) In order to effectively reduce the large-size calcium-containing spherical oxide inclusions in cold heading steel, it is necessary to find a technical method that can replace LF calcium treatment to solve the problem of molten steel continuous casting.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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