Formation Mechanism of Oxide Inclusions in Cr–Mn–Ni Stainless Steel

Jingyu LI,¹⁾ Guoguang CHENG,^{1)*} Liuyi LI,²⁾ Bin HU,²⁾ Changsong XU²⁾ and Guimin WANG²⁾

1) State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing, 100083 China.

2) Southwest Stainless Steel Co., Ltd., Sichuan Jinguang Group, Leshan, Sichuan, 106083 China.

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The evolution mechanism of oxide inclusions in Cr–Mn–Ni stainless steel was investigated by industrial trials and thermodynamic calculation. The morphology, composition, and size distribution of inclusions in steel specimens were analyzed by scanning electron microscopy and energy dispersive spectroscopy. During the LF refining process, there were mainly liquid Ca–Si–Mg–Al–O inclusions in molten steel deoxidized with FeSi alloy. Combined with the Al–Si–O phase diagram, the specimen compositions were also located in the liquid oxide phase. At the same Al content, increasing Si content could make the steel compositions in the liquid oxide phase to avoid the formation of Al_2O_3 . After continuous casting, the number density of Ca–Si–Mg–Al–O inclusions decreased to 1.81 mm^{-2} . On the contrary, the number density of Mn–(Al–Ti)–O inclusions increased to 4.62 mm^{-2} . The MnO contents of most Mn–(Al–Ti)–O inclusions were higher than 40%. The size of most Mn–(Al–Ti)–O inclusions was smaller than $3 \mu\text{m}$. The formation of these inclusions was consistent with thermodynamic calculation, which indicated that Mn–Al–O and Mn–Ti–O inclusions were formed during the solidification of Cr–Mn–Ni stainless steel. The effects of different Al and Ti contents on the formation of oxide inclusions during continuous casting process were discussed.

KEY WORDS: Mn–Al–O; Mn–Ti–O; solidification; thermodynamic calculation; inclusion.

1. Introduction

Nonmetallic inclusions have a significant effect on the final mechanical properties of steels. Most inclusions are detrimental to steel properties,^{1–5)} but beneficial effect of inclusions on phase transformation behavior has also been recognized and termed “oxide metallurgy”.^{6–8)} Nonmetallic inclusions can affect the grain size by acting as intragranular nucleation sites for acicular ferrite, which can reduce the grain size and improve the physical properties of steel.^{9–18)} Thus, the final product quality can be improved by controlling the composition and size of the nonmetallic inclusions in steelmaking.

Many scholars have studied the composition and size of oxide inclusions during the solidification of molten steel and the distribution characteristics of oxide inclusions in the solidification structure. Kiviö *et al.*¹⁹⁾ found that TiO_2 was first reduced to Ti_3O_5 in C–Mn–Cr liquid steel at high temperatures and then to Ti_2O_3 during cooling at around 1 573 K. Ohta H *et al.*²⁰⁾ studied the effect of Al_2O_3 , ZrO_2 , Ce_2O_3 , and MgO particles on the precipitation of TiN in Fe-10 mass%Ni alloy during solidification and holding at 1 673 K. The number density of TiN+MgO particles was higher than that of TiN+ M_xO_y ($\text{M}=\text{Al}$, Zr , or Ce) particles, while

the diameters of the former particles were smaller than those of the latter particles. They further investigated the characteristics of particle size distributions of inclusions in Fe-10 mass% Ni alloy deoxidized with Mg, Zr, Al, Ca, Mn/Si, and Al/Mg with the function of holding time, amount of deoxidant and order of deoxidant addition.^{21–23)} It was found that the spread of particle size distribution decreased in the order of $\text{Al}_2\text{O}_3 > \text{ZrO}_2 > \text{MgO} > \text{CaO} \cdot \text{Al}_2\text{O}_3 > \text{MnO} \cdot \text{SiO}_2$ particles.

Mn–Al–Ti–O inclusions have also attracted much attention. The Mn-depleted zone can form around the inclusions after proper thermal treatments, which promote the formation of the acicular ferrite.^{24–26)} What is more, titanium-containing inclusions are also well known to act as nucleation sites for acicular ferrite.^{27–34)} Park *et al.*³⁵⁾ have investigated the effect of Al on the evolution of non-metallic inclusions in the Mn–Si–Ti–Mg deoxidized steels during solidification. The major inclusion was the Mg–Ti–Al–O spinel phase of which composition was continuously changed from the Mg–Ti–O to MgAl_2O_4 with the increase of Al content in steels. However, the characteristics and formation mechanism of Mn–Al–Ti–O inclusions during continuous casting of Cr–Mn–Ni austenitic stainless steel have not been investigated.

In the present work, the samples taken at different stages in plant trial were investigated to reveal the characteristics and formation mechanism of oxide inclusions in Cr–Mn–Ni stainless steel. The morphology, composition, and size distribution of inclusions in steel specimens were determined

* Corresponding author: E-mail: chengguoguang@metall.ustb.edu.cn
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by scanning electron microscopy and energy dispersive spectroscopy. Combined with experimental results and thermodynamic calculations, the formation mechanism of Mn–(Al–Ti)–O inclusions during solidification of Cr–Mn–Ni stainless steel containing different Al and Ti contents were discussed.

2. Methodology

2.1. Experimental Procedures

The steelmaking process of Cr–Mn–Ni stainless steel was “70-ton EAF (Electric Arc Furnace)→ 70-ton GOR (Gas Oxygen Refining)→ 70-ton LF refining (Ladle Furnace)→Continuous casting (CC)”, as shown in **Fig. 1**. Steel scrap and alloys were initially melted in EAF. Then, the molten steel was decarburized, deoxidized, and desulfurized in GOR. FeSi alloy was added to deoxidize in GOR. In LF refining process, the chemistry and temperature of molten steel were fine-tuned. The argon bottom blowing flow rate was 100–150 NL/min. After 40–60 min treatment, the ladle with qualified molten steel was transported to the continuous casting platform for continuous casting. The temperature of the molten steel in tundish was 1 480°C. Continuous casting slab had been held in the heating furnace at 1 250°C for 60 minutes. Then the slab was rolled into hot-rolled sheet.

Steel samples were systemically taken at different stages, namely at the beginning of LF refining, at the end of LF refining, continuous casting slab, and hot-rolled sheet, respectively. The lollipop steel samples taken during LF refining process were immediately quenched in water. Schematic illustration of sampling locations was shown in **Fig. 1**.

2.2. Composition Analysis and Inclusion Characterization

The steel samples were cleaned by machining off the surface for chemical analysis. Cylinders ($\Phi 5\text{ mm} \times 5\text{ mm}$) were machined for the measurement of the total oxygen contents which were analyzed by the inert gas fusion-infrared absorptiometry method with an accuracy of $\pm 1\text{ ppm}$. The acid-soluble Al and Ti contents in steel were determined by the inductively coupled plasma optical emission spectrometry method (ICP-OES) with $\pm 5\text{ pct}$ relative standard deviation. The contents of C and S were analyzed by high frequency

Fig. 1. Schematic illustration of sampling locations.

Table 1. Chemical composition of steel samples (mass percent).

Sample No.	C	Si	Mn	S	Cr	Ni	Al	Ti	O
1	0.068	0.58	5.69	0.0019	17.44	3.56	0.0033	0.0038	0.0041
2	0.076	0.58	5.73	0.0011	17.55	3.58	0.0020	0.0038	0.0015
3	0.078	0.52	5.78	0.0011	17.28	3.63	0.0012	0.0035	0.0018
4	0.077	0.50	5.78	0.0011	17.37	3.62	0.0005	0.0028	0.0018

infrared carbon and sulfur analyzer (Type EMIA-920V2) with an accuracy of $\pm 0.5\text{ pct}$ relative standard deviation. The alloying element contents in steel were measured by the alkali fusion acid dissolution method. The chemical compositions of steel specimens were given in **Table 1**.

The morphology and composition of nonmetallic inclusions on the steel specimens were analyzed with the aid of an automatic scanning electron microscope (EVO18-INCAsteel, ZEISS Co. Ltd.) combined scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS). The maximum diameter of the inclusion was defined as the size of the inclusion. For the accuracy of automated EDS analysis of inclusions, the size was taken larger than $1\text{ }\mu\text{m}$, because the interaction volume may spread into the steel and excite electrons from the surrounding environment of the inclusions with diameters smaller than $1\text{ }\mu\text{m}$.

3. Results and Discussion

3.1. Characterization of Inclusions

After the addition of FeSi alloy to deoxidize in GOR, the main type of inclusions in sample 1 taken at the beginning of LF was spherical $\text{CaO-SiO}_2\text{-MgO-Al}_2\text{O}_3$, as shown in **Fig. 2(a)**. The Al_2O_3 and MgO contents in inclusions were much lower than that of CaO and SiO_2 contents. What is more, some inclusion contained a small amount of titanium oxide, as shown in **Fig. 3**. The slag and MgO -based refractory supplied soluble Mg to form MgO in inclusions.^{36–38} The aluminum and titanium in inclusions were mainly derived from FeSi alloy.^{39,40} The elemental mapping of a typical $\text{CaO-SiO}_2\text{-MgO-Al}_2\text{O}_3$ inclusion in sample 1 is

Fig. 2. Morphology and main composition of typical inclusions encountered in samples. (a) the typical inclusions at the beginning of LF refining, (b) the typical inclusions at the end of LF refining, (c) the typical inclusions in the continuous casting slab, (d) the typical inclusions in the hot-rolled sheet.

Fig. 3. SEM image and EDS spectra of a typical inclusion in sample 1 taken at the beginning of LF refining. (Online version in color.)

Fig. 4. Elemental mapping of typical inclusions at each stage. (a) a typical CaO–SiO₂–MgO–Al₂O₃ inclusion in sample 1, (b) a typical CaO–SiO₂–MgO–Al₂O₃ inclusion in sample 2, (c) a typical Mn–Al–Ti–O inclusion in sample 3, (d) a typical Mn–Al–Ti–O inclusion in sample 4. (Online version in color.)

shown in Fig. 4(a). It can be seen that the compositions of the inclusion without the distribution of Mn were homogeneous. At the end of LF, the types of inclusions in sample 2 were essentially same as that of sample 1, as shown in Fig. 2(b). The elemental mapping of a spherical homogeneous $\text{CaO-SiO}_2\text{-MgO-Al}_2\text{O}_3$ inclusion in sample 2 is shown in Fig. 4(b). Based on the spherical shape of these inclusions, it was clear that these inclusions were mainly liquid oxide during LF refining process. The liquid $\text{CaO-SiO}_2\text{-MgO-Al}_2\text{O}_3$ inclusions should be easier to remove from molten steel to slag. The agitation of argon gas in the liquid steel promoted the collision, coagulation and floating of inclusions, which led to the total oxygen content decrease from 41 ppm to 15 ppm during LF refining process. After the process of continuous casting, the inclusions in sample 3 were mainly Mn-(Al-Ti)-O inclusions (including Mn-Al-Ti-O , Mn-Al-O , and Mn-Ti-O) and a few amounts of spherical $\text{CaO-SiO}_2\text{-MgO-Al}_2\text{O}_3$ inclusions, as shown in Fig. 2(c). The elemental mapping of a typical Mn-Al-Ti-O inclusion is shown in Fig. 4(c). It can be seen that the compositions of the inclusion were heterogeneous. The size of Mn-(Al-Ti)-O inclusions in sample 3 was generally smaller than $4\text{ }\mu\text{m}$. What is more, some Mn-(Al-Ti)-O inclusions contained a small amount of sulfur element, as shown in Fig. 5. The major inclusions in sample 4 were Mn-(Al-Ti)-O inclusions (including Mn-Al-Ti-O , Mn-Al-O , and Mn-Ti-O), as shown in Fig. 2(d). These inclusions were mostly ellipsoidal or irregularly shaped, which was related to the deformation during the hot rolling process. The elemental mapping of a typical Mn-Al-Ti-O inclusion is shown in Fig. 4(d). It can be seen that the main compositions of manganese, aluminum, and titanium in the inclusion with a small amount of CaO-SiO_2 were homogeneous.

The inclusions were classified according to the type of inclusions observed above: Ca-Si-Mg-Al-O , Mn-Al-Ti-O , Mn-Al-O , and Mn-Ti-O . Figure 6 shows the percentages for different inclusions in all steel samples. During LF refining process, the percentages of Ca-Si-Mg-Al-O inclusions were 100%. After continuous casting, the percentage of Ca-Si-Mg-Al-O inclusions was reduced to 36% in sample 3. The percentages of Mn-(Al-Ti)-O inclusions were increased. The percentages of Mn-Al-Ti-O , Mn-Al-O , and Mn-Ti-O inclusions were 26%, 19%, and 20%, respectively. This indicated that Mn-(Al-Ti)-O inclusions were formed during continuous casting, which changed the main inclusions type from Ca-Si-Mg-Al-O to Mn-(Al-Ti)-O . After hot rolling, the percentage of Ca-Si-Mg-Al-O

decreased to 22%. At the same time, the percentages of Mn-Al-Ti-O , Mn-Al-O , and Mn-Ti-O inclusions increased to 30%, 27%, and 20%, respectively.

The size distribution of different inclusions in samples was counted, as shown in Fig. 7. The inclusions were divided by sizes: $1\text{--}2\text{ }\mu\text{m}$, $2\text{--}3\text{ }\mu\text{m}$, $3\text{--}4\text{ }\mu\text{m}$, $4\text{--}8\text{ }\mu\text{m}$, and larger than $8\text{ }\mu\text{m}$. After LF refining process, the number

Fig. 6. Different inclusions in steel samples. (Online version in color.)

Fig. 7. Size distribution of different inclusions in all samples. (Online version in color.)

Fig. 5. SEM image and EDS spectra of a typical inclusion in sample 3 taken from continuous casting slab. (Online version in color.)

density of Ca–Si–Mg–Al–O inclusions decreased from 2.18 mm^{-2} in sample 1 to 1.93 mm^{-2} in sample 2. The Ca–Si–Mg–Al–O inclusions further reduced to 1.81 mm^{-2} after continuous casting. Meanwhile, the number density of Mn–Al–Ti–O, Mn–Al–O, and Mn–Ti–O inclusions in sample 3 increased to 1.3 mm^{-2} , 2.31 mm^{-2} , and 1.01 mm^{-2} respectively. The size of these Mn–(Al–Ti)–O inclusions was smaller than $4 \mu\text{m}$. After hot rolling, the number density of Ca–Si–Mg–Al–O inclusions increased. As can be seen in Fig. 2(d3), some single inclusions were broken into discrete parts, which might lead to the increase of number density of inclusions in sample 4.^{41,42)} What is more, the size of these Ca–Si–Mg–Al–O inclusions in sample 4 was smaller than $8 \mu\text{m}$. The number density of Mn–Al–Ti–O, Mn–Al–O, and Mn–Ti–O inclusions in sample 4 further increased to 3.74 mm^{-2} , 3.40 mm^{-2} , and 2.48 mm^{-2} respectively. Most of these Mn–(Al–Ti)–O inclusions were smaller than $4 \mu\text{m}$.

Titanium has different oxidation state in molten steel depending on the titanium content in steel and the oxygen partial pressure, such as TiO, TiO₂, Ti₃O₅, Ti₂O₃, and Ti₄O₇.^{43,44)} According to the previous researchers, Ti₃O₅ was a stable deoxidized product in the present study.^{43–46)} To investigate the composition evolution of inclusions, the mass fraction of MnO, Ti₃O₅, Al₂O₃, CaO, SiO₂, and MgO of inclusions with various sizes are shown in Fig. 8. It can be seen in Fig. 7 that the size of most inclusions was

smaller than $8 \mu\text{m}$. Thus, the size of the inclusions taken into consideration in Fig. 8 ranged from $1 \mu\text{m}$ to $8 \mu\text{m}$. Figures 8(a) and 8(b) shows that the main compositions of inclusions in sample 1 and 2 were CaO and SiO₂. The CaO content in large size inclusions was generally higher than that of small size inclusions. The MgO, MnO, and Al₂O₃ contents of most inclusions were lower than 20% before continuous casting. In addition, only a few amounts of inclusions contained titanium oxide. After the process of continuous casting, the MnO, Al₂O₃, and Ti₃O₅ contents in sample 3 and 4 were significantly increased, as shown in Figs. 8(c) and 8(d). The newly formed Mn–(Al–Ti)–O inclusions during continuous casting and the removal of liquid CaO–SiO₂ inclusions before continuous casting might lead to the decrease of the concentration of CaO and SiO₂. While the CaO and SiO₂ contents of most inclusions in sample 2 were higher than 30%, the CaO and SiO₂ contents of most inclusions in sample 3 were lower than 30%. The MnO contents of most Mn–(Al–Ti)–O inclusions were higher than 40%. Moreover, most of the Mn–(Al–Ti)–O inclusions were smaller than $3 \mu\text{m}$. After hot rolling, the number of Mn–(Al–Ti)–O inclusions was obviously increased, which might due to the deformation of inclusions or the formation of inclusions during hot rolling process.

Fig. 8. The evolution of the main compositions of inclusions in all samples with various sizes: (a) the inclusions in sample 1, (b) the inclusions in sample 2, (c) the inclusions in sample 3, (d) the inclusions in sample 4. (Online version in color.)

3.2. Thermodynamic Calculation of Inclusion Formation

The main inclusions in the refining process were Ca–Si–Mg–Al–O inclusions, in which Ca and Mg of the inclusions were mainly derived from refractory and slag.^{36–38)} Meanwhile, the aluminum in the inclusions was usually derived from the residual elements in the FeSi alloy, and the residual elemental aluminum has an important influence on the formation of inclusions in the silicon deoxidized stainless steel. Thus, the phase stability diagram of Al–Si–O system in Fe-17.5Cr-3.5Ni-5.5Mn steel at 1 600°C was calculated with the aid of FactSageTM 7.2 software, as shown in Fig. 9. The phase diagram can be divided into three regions: alumina, liquid oxide, and liquid steel. The silicon and aluminum contents in the phase diagram range from 0.01 to 2 mass% and 1 ppm to 0.1 mass%. The boundary lines of each phase field were evaluated using [O] ppm as a parameter. Excessively high residual Al coming from FeSi alloy in molten steel would cause the steel composition to be located in the Al₂O₃ region, which would lead to the nozzle clogging and surface defects of final product.^{3,47,48)} It can be seen from the Fig. 9 that increasing the silicon content in the steel under the same aluminum content causes the steel composition to enter the liquid oxide region from the alumina region, which means that increasing the silicon content can avoid the formation of alumina. In this experiment, the steel compositions were all located in the liquid oxide area, and most of the inclusions were liquid oxide. Alumina inclusions were not observed which facilitates the continuous casting and the quality of the final stainless steel product.

The main inclusions changed from Ca–Si–Mg–Al–O inclusions during LF refining to Mn–(Al–Ti)–O inclusions after continuous casting. The Mn-depleted zone can form around the Mn-containing inclusions after proper thermal treatments, which promote the formation of the acicular ferrite.^{24–26)} Meanwhile, titanium-containing inclusions are also well known to act as nucleation sites for acicular ferrite.^{27–34)} Thus, these Mn–(Al–Ti)–O inclusions formed during continuous casting could be used to promote the formation of acicular ferrite in further industrial production.

Fig. 9. Stability diagrams of Al–Si–O system with iso-oxygen contours in Fe-17.5Cr-3.5Ni-5.5Mn at 1 600°C. (Online version in color.)

Therefore, to investigate the formation mechanism of the Mn–(Al–Ti)–O inclusions during the process of continuous casting, equilibrium precipitation of inclusions during solidification of steel was calculated by using FactSageTM 7.2 software with FactPS, FToxid, and FSstel databases, as shown in Fig. 10(a). Sample 3 was taken as the initial compositions of steel to calculate. It can be seen from Fig. 10(a) that the liquid steel began to solidify at 1 425°C in conjunction with the formation of δ -ferrite (BCC). γ -austenite (FCC) began to form at 1 380°C. Liquid steel completely disappeared at 1 355°C. During the solidification of molten steel, two kinds of inclusions were formed, namely Mn–Al–O and Mn–Ti–O. Mn–Al–O was formed at 1 425°C. Mn–Ti–O was formed at 1 405°C lower than the liquidus temperature (1 425°C). The amount of Mn–Al–O and Mn–Ti–O increased with the decrease of temperature during solidification. When the temperature was lower than 1 425°C, the Mn–Al–O and Mn–Ti–O contents were almost stable with the decrease of temperature. The main compositions of Mn–Al–O and Mn–Ti–O inclusions are also shown in Fig. 11. It can be seen in Fig. 11(a) that the Al₂O₃ and MnO contents of Mn–Al–O inclusions also increased with the decrease of temperature. In addition, the Al₂O₃ content was higher than the MnO content of Mn–Al–O inclusions during solidification process. As for Mn–Ti–O inclusion, the MnO content was higher than TiO_x content, as shown in Fig. 11(b). At the same time, the trend of the change of MnO and TiO_x contents was consistent with the Mn–Ti–O inclusion during solidification. The formation of Mn–Al–O and Mn–Ti–O inclusions during continuous casting caused the main inclusions observed in continuous casting slab, and hot-rolled sheet to be Mn–(Al–Ti)–O inclusions. In addition, the equilibrium precipitations of inclusions under different conditions of Al and Ti contents were further calculated, as shown in Fig. 10. After improving the Al content to 30 ppm, the main inclusions formed during continuous casting were Al₂O₃, as shown in Fig. 10(b). The Al₂O₃ inclusions were formed at 1 470°C. The amount of Al₂O₃ inclusions increased with the decrease of temperature. When the temperature was lower than the solidus temperature (1 355°C), the amount of Al₂O₃ inclusions was constant. When the titanium content was increased to 50 ppm in molten steel containing 10 ppm Al, the Mn–Al–O inclusions were still formed during continuous casting, as shown in Fig. 10(c). The formation temperature of Mn–Ti–O inclusions was 1 420°C in Fig. 10(c), which was higher than the formation temperature of Mn–Ti–O inclusions in Fig. 10(a). As the temperature decreased, the content of Mn–Ti–O inclusions exceeded the content of Mn–Al–O inclusions at 1 400°C in Fig. 10(c). When the temperature was lower than 1 350°C, the change tendency of the content of Mn–Al–O and Mn–Ti–O inclusions in steel containing 50 ppm Ti and 10 ppm Al was basically same as that in steel containing 30 ppm Ti and 10 ppm Al. The compositions of oxide inclusions in Fig. 10(c) are also plotted in Figs. 11(c) and 11(d). As the titanium content increased to 50 ppm, the TiO_x content of Mn–Ti–O inclusion increased in Fig. 11(d), which was higher than the TiO_x content of Mn–Ti–O inclusion in Fig. 11(b). Meanwhile, although the molten steel contained 50 ppm Ti, Mn-containing inclusions and Ti-containing inclusion would disappear under higher Al content (30 ppm), as

Fig. 10. Equilibrium precipitations of inclusions during solidification of Cr-Mn-Ni stainless steel: (a) 0.0035Ti-0.0010Al; (b) 0.0035Ti-0.0030Al; (c) 0.0050Ti-0.0010Al; (d) 0.0050Ti-0.0030Al. (Online version in color.)

Fig. 11. Compositions of MnO, Al_2O_3 and TiO_x in oxide inclusions during solidification of Cr-Mn-Ni stainless steel: (a) compositions of Mn-Al-O inclusions and (b) compositions of Mn-Ti-O inclusions in steel containing 0.0035Ti-0.0010Al; (c) compositions of Mn-Al-O inclusions and (d) compositions of Mn-Ti-O inclusions in steel containing 0.0050Ti-0.0010Al. (Online version in color.)

shown in Fig. 10(d). Thus, it can be found that when the aluminum content in the steel was too high, alumina inclusions were the main inclusions formed during continuous casting process, and Mn-(Al-Ti)-O inclusions cannot be formed.

4. Conclusions

The objective of the present work was to investigate the formation mechanism of oxide inclusions in Cr-Mn-Ni stainless steel. According to the analysis of inclusion characteristics and thermodynamic calculation, the following conclusions were drawn.

(1) During the LF refining process, there were mainly spherical Ca-Si-Al-Mg-O inclusions in molten steel deoxidized with FeSi alloy. After continuous casting, the number density of Ca-Si-Al-Mg-O inclusions decreased to 1.81 mm^{-2} . In contrast, the number density of Mn-(Al-Ti)-O inclusions increased to 4.62 mm^{-2} . The MnO contents of most Mn-(Al-Ti)-O inclusions were higher than 40%. The size of most Mn-(Al-Ti)-O inclusions was smaller than $3 \mu\text{m}$.

(2) Liquid oxides were the main inclusions during LF refining. Combined with the Al-Si-O phase diagram, the specimen compositions were also located in the liquid oxide phase. At the same Al content, increasing Si content made the steel compositions in the liquid oxide phase to avoid the formation of Al_2O_3 .

(3) Both the characteristics of inclusions and thermodynamic calculation indicated that the compositions of inclusions in steel specimens after continuous casting were mainly Mn-(Al-Ti)-O inclusions. During the continuous casting process of Cr-Mn-Ni stainless steel, Mn-Al-O and Mn-Ti-O inclusions would be precipitated. In addition, increasing the Al content to 30 ppm would result in the formation of Al_2O_3 rather than Mn-(Al-Ti)-O during continuous casting process.

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