Formation Mechanism of Large-size $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ Inclusions in High Carbon Chromium Bearing Steel

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Industrial experiments and thermodynamic analyses were carried out to investigate the formation mechanism of large-size ($> 30 \mu\text{m}$) $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ (CAMS) inclusions in high carbon chromium bearing steel. It was found that the large-size CAMS inclusions existed during the whole refining process, most of which compositions were located in the liquid region. The average content of SiO_2 in CAMS inclusions decreased from 27.5 mass% at argon-blowing station to 3.0 mass% in the hot-rolled bars. The results calculated by Factsage 7.3 indicated that the CAMS inclusions were originated from slag entrapment. During BOF tapping, the low basicity slag with 60 mass% SiO_2 was entrapped into steel and combined with the deoxidation product Al_2O_3 , forming a large amount of liquid CAMS inclusions. During LF refining process, [Al], [Ca] and [Mg] in molten steel were affected by the activities of corresponding slag components. The reaction between these three elements and SiO_2 in CAMS inclusions originating from slag lead to the decrease of SiO_2 in the inclusions. Due to the low interfacial energy between liquid CAMS inclusions and steel, a few large-size inclusions may be inherited to hot-rolled bars. In light of this, several optimization steps were conducted during BOF tapping and argon-blowing station. After the optimization, large-size CAMS originated from BOF tapping were effectively removed.

KEY WORDS: bearing steel; large-size inclusions; $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$; formation mechanism; slag entrapment; thermodynamics.

1. Introduction

High carbon chromium bearing steel is one of typical high carbon bearing steel, widely used various facilities requiring high contact fatigue strength. In recent years, the typical impurities, *i.e.* oxygen, titanium, already could be well controlled at extremely low levels with the continuous improvement of metallurgical technology. In this case, the threaten of large-size inclusions ($> 30 \mu\text{m}$) has been one of the leading threatens to rolling contact fatigue (RCF) life of bearing steel.¹⁾ The inclusions usually act as the early origin of fatigue defects, which will accelerate the fatigue spalling of rolling surface.²⁾ As the largest inclusion in steel, the large-size inclusions ($> 30 \mu\text{m}$) usually are CaO -containing inclusions with two-dimensional morphology close to circle. When these inclusions contain SiO_2 , their melting point will be lower resulting in larger size of inclusions and greater harm to steel. Therefore, a thorough understanding of formation mechanism of these inclusions is crucial for producing superior bearing steel.

During past decades, several researchers have contributed to the formation of endogenous inclusions of bearing steel.^{3–6)} The deoxidation product Al_2O_3 will react with the dissolved Mg in molten steel forming $\text{MgO-Al}_2\text{O}_3$ inclusions at the beginning of ladle refining. As the slag-metal reaction proceeds, the spinel inclusions will react with dissolved Ca and transform into $\text{CaO-MgO-Al}_2\text{O}_3$ inclusions. However, the large-size inclusions ($> 30 \mu\text{m}$) occasionally occur, not only affected by metallurgical process such as slag entrapment caused by unreasonable argon blowing system, but also by the addition of slagging agent,^{7,8)} deoxidizer^{9,10)} and usage of refractory materials of ladle and tundish.^{11,12)} The formation of the large-size inclusions has become the hotspot for bearing steel. Ohta *et al.*¹³⁾ added a tracer element to the top slag prior to the LF treatment and identified the main origin of the CaO containing inclusions is LF top slag entrapped during gas stirring. Kawakami *et al.*¹⁴⁾ found that the Al_2O_3 inclusions are also formed by desulfurization reaction after deoxidation, and the $\text{CaO-Al}_2\text{O}_3$ inclusions are formed by two reactions. One is the intrinsic reaction of Al in molten steel and CaO in slag. Another is the reaction of Ca in molten steel and Al_2O_3 in

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inclusion. Beskow *et al.*¹¹⁾ found that the ladle glaze is one of the major sources of CaO–Al₂O₃ inclusions during the degassing and flotation periods of ladle treatment. Wang *et al.*¹⁵⁾ analyzed the characteristics of inclusions from LF to billet and found that the reoxidation during continuous casting is the main factor to determine the formation of large-size CaO–MgO–Al₂O₃ inclusions. Zhu *et al.*¹⁶⁾ pointed out that the inclusions from nozzle clogging is the source of large-size CaO–MgO–Al₂O₃ inclusions in bearing steel bars. These studies described well the source of large-size CaO–MgO–Al₂O₃ inclusions in different factories, but there are few studies on the large-size inclusions containing SiO₂ in bearing steel. Therefore, more detailed analysis about the large-size CAMS inclusions should be concerned.

In the present study, the formation mechanism of large-size CAMS inclusions is fully investigated. The characteristics of large-size inclusions in rolled bars and refining process were analyzed by SEM and EDS. The source of CAMS inclusions was identified by thermodynamic calculation and mathematical model. Based on these results, some optimization methods are proposed to reduce the formation of large-size CAMS inclusions.

2. Experimental

2.1. Experimental Procedure

High carbon chromium bearing steel was produced by the process of 130 t BOF (Basic Oxygen Furnace)→AS (Argon-blowing Station)→LF (Ladle Furnace refining)→RH (RH vacuum degassing)→CC (Continuous Casting). The argon-blowing station is used for temperature and composition homogenization of molten steel, inclusions floatation promotion in advance. During BOF tapping, lime and low basicity slag with about 60 mass% SiO₂ were added. At the beginning of ladle refining, synthetic slag (CaO–Al₂O₃) was added. During the refining process, five samples including steel and slag named as “Argon-blowing Station (AS)”, “LF1”, “LF2”, “RH1”, “RH2” were sampled. **Figure 1**

Table 1. Chemical compositions of low basicity and synthetic slag, mass%.

Raw slag	CaO	MgO	Al ₂ O ₃	SiO ₂
low basicity slag	31.5±2.0	≤1.5	≤3	61±2.0
synthetic slag	47–53	3–8	33–36	≤6

shows the schematic diagram of production process and sampling. **Table 1** lists the compositions of low basicity slag and synthetic slag. In addition, five 15×15×15-mm cubic samples were cut from the hot-rolled bars for the microscopic observation.

2.2. Chemical Analysis and Microscopic Observation

The acid-soluble Al, Ca, Si, Mn and Mg contents in steel were determined by the inductively coupled plasma optical emission spectrometry method (ICP-OES). The content of total oxygen was measured by the inert gas fusion-infrared absorptiometry. The compositions of slag samples were determined by an X-ray fluorescence spectrometer. All the obtained steel samples were ground and mirror polished for inclusion inspection. SEM and EDS were used to analyze the morphologies and compositions of inclusions in the steel sample. The observation range of each sample is a circle with a diameter of 15 mm. The maximum diameter of the inclusion was defined as the size of the inclusion. The large-size (>30 μm) inclusions in hot-rolled bars that could directly lead to unqualified products were analyzed. In particular, the characteristics of inclusions in the refining process were analyzed especially with a size greater than 13 μm with reference to the rating standards for non-metallic inclusions of DS.¹⁷⁾ This method can not only cover the large-size (>30 μm) inclusions, but also obtain more statistical data, which is more reasonable for analysis and discussion.

3. Results

3.1. Chemical Compositions of Steel and Slag

Table 2 lists the chemical compositions of various steel samples. Each element was tested for four times. Only one value was listed in the table if the results were all the same. All the different values were listed in the table and separated by “/” if the results were different. It can be seen that the contents of Al, Mg, Ca and oxygen fluctuates greatly at argon-blowing station, indicating there may exist large-size inclusions. In addition, the content of Al decreases during LF refining process, indicating that deoxidation reaction continuously proceeds. **Table 3** lists the chemical compositions of various slag samples. It can be seen that the content of SiO₂ in slag of argon-blowing station is relatively high with the value of 12.3 mass% due to the addition of low basicity slag. After the addition of synthetic slag, the content

Fig. 1. Schematic diagram of the production process and sampling.

of SiO₂ in slag decreases to 8.32 mass%.

3.2. Characteristics of Large-size CaO–Al₂O₃–MgO–SiO₂ Inclusions in Hot-rolled Bars

Large-size (>30 μm) inclusions in hot-rolled bars were analyzed by SEM and EDS. It was found that all the large-size inclusions are CAMS inclusions. As shown in the Fig. 2, the SiO₂ content in the two typical CAMS inclusions are 7.86 mass% and 2.61 mass%, respectively. These large-size

inclusions are approximately circular in two-dimensional morphology and the liquidus temperatures calculated by FactSage 7.3 are 1 774 K and 1 755 K which indicates that these inclusions are liquid oxides in molten steel. Ca, Mg, Al, Si and O elements are almost homogeneously distributed throughout the whole inclusion which is wrapped by CaS. The large-size CAMS inclusions in hot-rolled bars are tens to hundreds microns which can seriously shorten the fatigue life of bearing steel.

3.3. Characteristics of Inclusions during Refining Process

In order to identify the source of large-size inclusions in the hot-rolled bars, the characteristics of the inclusions especially with sizes more than 13 μm in whole refining process were analyzed. Most of large-size inclusions are CAMS inclusions. The morphology, elemental mappings of typical CAMS inclusions are shown in Fig. 3. It can be seen that the Ca, Al, Si, Mg and O are homogeneously distributed. What's more, typical inclusions of different stages are almost round in two-dimensional morphology which indicates that these inclusions are liquid in molten steel. The sizes of these large-size inclusions range from tens to hundreds microns. The content of SiO₂ in CAMS inclusions of argon-blowing station is 21.77 mass% (Fig. 3(a)). This kind of CAMS inclusions could not come from the fully melted slag of argon-blowing station because the content of SiO₂ in it is only 12.3 mass% (Table 3). Figure 4 is the projected ternary phase diagram of CaO–Al₂O₃–SiO₂ at 1 600°C showing the major compositions of inclusions larger than 13 μm in different stages, from which it can be seen that most of inclusions fall into the liquid region. At argon-blowing station, the content of SiO₂ in inclusions

Table 2. Chemical compositions of steel, mass%.

Stage	Al,%	Ca,ppm	Mg,ppm	Si,%	Mn,%	O,ppm
Argon-blowing Station	0.068/ 0.054/0.048	6/580/ 210/50	4/56/90/13	0.17	0.20	148/46/398
LF1	0.030	7	5	0.19	0.30	31/27/16/30
LF2	0.025	7	5	0.20	0.34	28/42/92/55
RH1	0.020	7	5	0.23	0.34	10/25/41
RH2	0.017	<2	4	0.20	0.34	27/10/16
Hot-rolled Bar	0.016	2	4	0.20	0.34	5

Table 3. Chemical compositions of slag, mass%.

Stage	Al ₂ O ₃	CaO	MgO	SiO ₂	MnO	FeO
Argon-blowing Station	22.2	56.5	4.66	12.3	0.213	0.684
LF1	24.3	59.9	3.57	8.32	0.0438	0.678
LF2	25.2	59.3	3.64	8.08	0.0437	0.601
RH1	25.6	56.4	5.02	8.85	0.0676	0.767
RH2	23.9	54.1	4.29	12.9	0.115	1.47

Fig. 2. Typical morphologies and element mapping of large-size inclusions in hot-rolled bars. (Online version in color.)

Fig. 3. Typical morphologies and element mapping of inclusions (a) argon-blowing station (b) LF (c) RH during refining process. (Online version in color.)

Fig. 4. Main composition distribution of inclusions in different stages. (Online version in color.)

Fig. 5. Mass fraction of SiO_2 in $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ inclusions. (Online version in color.)

range from 7.88 mass% to 63.41 mass%, while the content of Al_2O_3 is mainly concentrated in the range of 10 mass% to 30 mass%. The large-size CAMS inclusions exist during

the whole process of refining. The content of SiO_2 in each inclusion and the average value of SiO_2 content in CAMS inclusions in each stage are shown in Fig. 5. It can be seen

Fig. 6. Total area of inclusions in different refining stages. (Online version in color.)

that the average of SiO_2 in CAMS inclusions shows a downward trend decreasing from 27.5 mass% at argon-blowing station to 3.0 mass% in hot-rolled bars.

Since the observed two-dimensional morphology of large-size inclusions is close to circular, it is assumed that the two-dimensional morphology of inclusions is circular and the maximum diameter is the diameter of the inclusion. Thus, the area of each inclusion and the total area of inclusions in each stage could be obtained. Figure 6 shows the total areas of inclusions and the average diameter and number of inclusions in different refining stages. The $\text{CaO-Al}_2\text{O}_3\text{-MgO}$ inclusions are the inclusions only containing CaO , Al_2O_3 and MgO . The $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ inclusions are the inclusions containing CaO , Al_2O_3 , MgO and SiO_2 . It can be seen that the inclusions in the argon-blowing station are all CAMS inclusions and the total area is as large as $35\,483\,\mu\text{m}^2$. This is not only related to the large number of inclusions, but also related to the large size of most inclusions which are more than $40\,\mu\text{m}$. During the LF and RH processes, the total area of inclusions first increased and then decreased. At the end of LF, the total area of inclusion is the largest. The reason may be that the number of inclusions in the same sampling position of upper molten steel increases due to the floatation of inclusions. The area of CAMS inclusions accounts for a high proportion of the total area in LF1 (84%), LF2 (99%) and RH1 (91%) stages which shows that CAMS inclusions are major inclusions during the refining process.

By analyzing the characteristics of inclusions with sizes more than $13\,\mu\text{m}$ in the refining process, it was found that the CAMS inclusions first occurred in the argon-blowing station. Additionally, this kind of inclusions have clear heritability and existed in hot-rolled bars.

4. Discussions

4.1. Source of Large-size Inclusions

4.1.1. Thermodynamic Calculation

In order to determine whether the large-size inclusions are endogenous inclusions or exogenous inclusions, the Equilib module of FactSage 7.3 was used to calculate the composition of liquid inclusions in equilibrium with liquid steel, as shown in Fig. 7. The calculated composition of molten steel is set as $\text{Fe-1.0C-0.2Si-0.35Mn-0.015P-0.0015S-0.0002Ca-0.0004Mg-0.0007 O-xAl}$ (mass fraction). This is the composition of molten steel in tundish and is closest to

Fig. 7. Amount of liquid inclusion and its component equilibrate with $\text{Fe-1.0C-0.2Si-0.35Mn-0.015P-0.0015S-0.0002Ca-0.0004Mg-0.0007 O-xAl}$ at $1\,600^\circ\text{C}$. (Online version in color.)

the composition of hot-rolled bars. However, the sample in tundish was not obtained successfully. The composition of molten steel in tundish was obtained by referring to that of other actual production process with same smelting process. It can be seen from Fig. 7 that liquid inclusions containing SiO_2 can be formed in molten steel only when the content of Al is more than 0.008 mass%. With the increase of Al, the SiO_2 in liquid inclusions in equilibrium with liquid steel decreases. During the real refining process, the content of Al in the molten steel is more than 0.015 mass%, and the SiO_2 content in the liquid inclusions in equilibrium with the liquid steel should be less than 2.4 mass%. Additionally, the content of Ca, O and Mg in molten steel might be larger than 2 ppm, 7 ppm and 4 ppm which could result in lower SiO_2 in inclusions. The content of SiO_2 in most of the CAMS inclusions are more than that in the liquid inclusions in equilibrium with the liquid steel which indicates the CAMS inclusions are obviously exogenous inclusions in molten steel.

4.1.2. Slag Entrapment Mathematical Model

A mathematical model was used to confirm the large-size CAMS inclusions are exogenous inclusions concerning the size of inclusions. According to the theoretical calculation

model of entrapped slag size established by Wei *et al.*,¹⁸⁾ when the actual velocity u_i (m/s) of steel-slag interface is greater than the critical velocity $u_{i,crit}$ (m/s), the slag will be entrapped in the molten steel, $u_{i,crit}$ can be obtained by the following formula:

$$u_{i,crit} = \left(\frac{8}{\rho_s} \right)^{\frac{1}{2}} \left[\frac{2}{3} \sigma g (\rho_m - \rho_s) \cos \alpha \right]^{\frac{1}{4}} \dots \dots \dots (1)$$

where the average slag composition of that in all stages is selected as the slag composition for calculation, ρ_s is slag density and 2 684 kg/m³,^{19,20)} σ is interfacial tension and 1.27 N/m,²¹⁾ g is gravity acceleration and 9.8 m/s², ρ_m is liquid steel density and 6 955 kg/m³ calculated by ProCAST software at 1 600°C, α is the angle between direction of inertial force and the vertical, taking 30°. ²²⁾ Thus $u_{i,crit}$ is 0.72 m/s.

The calculation formula of the average diameter of entrapped slag is as follows:

$$d_i = \frac{3}{8} \frac{\rho_s u_i}{g (\rho_m - \rho_s) \cos \alpha} \left\{ 1 - \left[1 - \frac{128}{3} \frac{\sigma g (\rho_m - \rho_s) \cos \alpha}{\rho_s^2 u_i^4} \right]^{\frac{1}{2}} \right\} \dots \dots \dots (2)$$

where d_i is the average diameter of entrapped slag (m). The average diameter of entrapped slag at different steel-slag interface velocities is shown in Fig. 8. It can be seen that when the velocity of steel-slag interface is greater than 0.72 m/s, the slag will be entrapped in the molten steel. With the increase of velocity, the size of entrapped slag becomes smaller. During the whole process, the argon flow rate is less than 80 Nm³/h, so the velocity of steel-slag interface is less than 3.3 m/s^{18,23)} and the average diameter of entrapped slag is more than 30 μ m. The large-size CAMS inclusions in hot-rolled bars are all larger than 30 μ m which is in good agreement with the calculated results. These results indicate that large-size CAMS inclusions are exogenous inclusions.

The heredity of the key element Si in the inclusions suggested that the large-size CAMS inclusions originated from slag entrapment during BOF tapping. This will be discussed

in detail in Section 4.3. Viscosity of slag is an important physical property which impacts the kinetic reactions during metallurgical processes.^{24–26)} The high viscosity of low basicity slag can affect the refining process. Table 1 shows that the main compositions of low basicity slag are CaO and SiO₂ and the mass fraction of SiO₂ is about 66% of these two compositions. To investigate the impacts of SiO₂ on the viscosity of the CaO–SiO₂ system, the measured values were extracted from previously published articles^{27–29)} and the calculated values were obtained by FactSage 7.3. All the data are plotted on Fig. 9. The results indicate that the viscosity of CaO–SiO₂ slag increases with the increase of the content of SiO₂ exponentially. For example, when the content of SiO₂ increases from 44% to 62% at 1 600°C, the slag viscosity changes from 0.11 Pa·s to 1.2 Pa·s,²⁷⁾ showing an order of magnitude change. The calculated viscosity of low basicity slag is 1.55 Pa·s (Fig. 9), and the extremely high viscosity slag after melting will result in the incrustation and poor fluidity of slag. This kind of slag will also result in the exposure of molten steel which is harmful to refining process.

4.2. Formation Mechanism of Large-size Inclusions

During the process of BOF tapping, Al deoxidizer was added firstly, it would react with oxygen in molten steel rapidly to form Al₂O₃. Then the low basicity slag and lime were added. Due to the high viscosity of melted low basicity slag, it could not be well mixed with CaO. In addition, the stirring of liquid steel was very violent. Therefore, some low basicity slag would be entrapped in the molten steel. CAMS inclusions were formed after the low basicity slag was combined with Al₂O₃, and the average content of SiO₂ in inclusions was as high as 27.5 mass%. During the process of argon-blowing station, the blowing flow was still high to enhance the stirring of molten steel and speed up the slag melting. However, this might also lead to the slag entrapped into the molten steel^{30,31)} resulting in the formation of a large number of CAMS inclusions. The viscosity of slag was still high at the beginning of LF and the synthetic slag was added to adjust slag fluidity under this condition.

Fig. 8. The average diameter of entrapped slag at different steel-slag interface velocities. (Online version in color.)

Fig. 9. The viscosity for the CaO–SiO₂ system at 1 600°C. (Online version in color.)

Meanwhile, the stirring strength was strong to promote the slagging and alloying which also might entrap the slag into the molten steel.

With the progress of refining, [Al], [Ca] and [Mg] in molten steel would react with SiO₂ in large-size inclusions, so the content of SiO₂ in inclusions gradually decreased with the refining progress (Fig. 5). The reaction equations are as follows:

where the subscript “inc” represents the composition in large-size CAMS inclusions. The activities of [Al] and [Ca] in molten steel are mainly affected by the activities of Al₂O₃ and CaO in slag. The activity of [Mg] is affected by both the slag and the refractory. In order to verify the influence of the activity change of slag component on the content change of inclusion component, the activity of Al₂O₃, CaO and MgO in CaO–Al₂O₃–MgO–SiO₂–MnO–FeO slag system at different refining stages at 1 600°C was calculated by ion and molecule coexistence theory (IMCT).³²⁾ The results are shown in Fig. 10. It can be seen that the activity of CaO increases first and then decreases, while the activity of Al₂O₃ changes in the opposite way, and the activity of MgO fluctuates slightly. The variation of average mass fraction of Al₂O₃, CaO and MgO in large-size CAMS inclusions during refining process is shown in Fig. 11. Compared with the activity changes of Al₂O₃, CaO and MgO in slag, it was found that the change of composition in inclusions lags behind the change of activities in slag, and there is a good corresponding relationship between them. For example, from argon-blowing station to LF1, CaO activity in slag increased first and decreased after LF1, while CaO content in inclusions increased from argon-blowing station to LF2, and decreased after LF2. The main reason is that the change of CaO activity in the slag first causes the change of [Ca] content at the interface of steel-slag. It takes a certain time for [Ca] element to diffuse and react with SiO₂ in inclusions, so the change of composition in inclusions lags behind the

Fig. 10. Activity of CaO and Al₂O₃ in CaO–Al₂O₃–MgO–SiO₂–MnO–FeO refining slag. (Online version in color.)

change of activities in slag. Due to the difference in initial SiO₂ content in large-size inclusions, the SiO₂ content of large-size inclusions in hot-rolled bars is also different.

CAMS inclusions are liquid in molten steel. Those inclusions have better wettability with molten steel (contact angle less than 65 degree^{33–35)}) than solid inclusions, poor collision and agglomeration capabilities and low floating removal rate, and tend to remain in molten steel. Thus, these inclusions have clear heritability and form large-size inclusions in hot-rolled bars. The schematic of formation mechanism of large-size CAMS inclusions is shown in Fig. 12.

4.3. Process Optimizations

Based on the previous results, we proposed the flowing methods to optimize the production process. Figure 13 shows the schematic diagram of optimization. Slag adding method was changed to avoid the poor slagging effect and slag entrapment caused by the addition of low basicity slag. The synthetic slag was added during the BOF tapping process in advance and the addition of low-basicity slag was cancelled. Under good slagging conditions, the synthetic slag showed excellent fluidity after melting compared with non-fully melted slag before optimization (Fig. 14). The alloy and slag were added separately with constant time

Fig. 11. Average mass fraction of CaO and Al₂O₃ in CaO–Al₂O₃–MgO–SiO₂ inclusions. (Online version in color.)

Fig. 12. Schematic of formation mechanism of large-size CaO–Al₂O₃–MgO–SiO₂ inclusions. (Online version in color.)

interval (60 s) to avoid the mix of them. The basicity of slag (CaO/SiO_2) was controlled between 5 and 9, while the Al_2O_3 was controlled in the range of 23 mass%–28 mass%. This

Fig. 13. Schematic diagram of optimization. (Online version in color.)

Fig. 14. Slagging effect after argon-blowing station before and after optimization. (Online version in color.)

Fig. 15. The number and size of inclusions before and after optimization (a) inclusion number (b) inclusion size. (Online version in color.)

can adjust the fluidity of the slag and ensure the effective absorption of inclusions by the slag. The argon flow rate was adjusted to soft blowing state (less than $30 \text{ Nm}^3/\text{h}$) to ensure the slag evenly spread on the surface of molten steel, as well as to avoid the exposure of molten steel at the later stage of argon-blowing station.

Figure 15 shows the number and size of inclusions during refining process before and after the optimization. The sampling and observation standards before and after optimization are the same. One sample was taken at each stage, and the observation range of each sample was a circular surface with a diameter of 15 mm. Figure 15(a) shows that the quantity of large-size inclusions in each refining stage after optimization was lower than that before the optimization. The total number of large-size inclusions during refining process decreased from 49 to 20. From Fig. 15(b) we can see that the size of inclusions also became smaller. Especially, there were no inclusions larger than $65 \mu\text{m}$ after optimization.

After the optimization, there was a significant reduction of the quantity of the inclusions and the sizes of these inclusion were smaller. From Fig. 16 we can see that the type

Fig. 16. Total area of inclusions in different refining stages after optimization. (Online version in color.)

of inclusions in argon-blowing station was changed from $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ before the optimization to Al_2O_3 (the content of Al_2O_3 in inclusion is more than 95 mass%) after the optimization. This is because the adding of low basicity slag was cancelled and combination of low basicity slag and Al_2O_3 reduced. The total area of CAMS inclusions was significantly reduced in the initial stage. The main type of inclusions changed to $\text{CaO-Al}_2\text{O}_3\text{-MgO}$ inclusions at the early stage of RH. After the optimization, the total area of all inclusions during refining process was $18\,197\,\mu\text{m}^2$ (Fig. 16), accounting for only 10% of $180\,976\,\mu\text{m}^2$ before the optimization (Fig. 6). The optimization effect in refining process is obvious and the main reason is that the number and size of large-size CAMS inclusions was significantly reduced during refining process. By comparing the test data of hot-rolled bars of six months before and after optimization, it was found that the qualified rate of inclusions within $30\,\mu\text{m}$ increased from 94% before optimization to 98.4% after optimization. By reducing the number of large-size CAMS inclusions during BOF tapping, the number of these inclusions was significantly reduced during refining process and in hot-rolled bars. These results suggest that the large-size CAMS inclusions in hot-rolled bars are mainly from the slag entrapment during BOF tapping.

5. Conclusions

In present study, the formation mechanism of large-size $\text{CaO-Al}_2\text{O}_3\text{-MgO-SiO}_2$ inclusions in bearing steel was investigated. The characteristics of inclusions were analyzed and the source of inclusions was identified. The following conclusions were obtained.

(1) The large-size inclusions in hot-rolled bars are CAMS inclusions. The morphology of these inclusions is approximately circular and the sizes are tens to hundreds of microns. The inclusions are wrapped by CaS and the compositions are uniformly distributed.

(2) CAMS inclusions mainly come from the slag entrapment during BOF tapping. With the refining process, the SiO_2 content in inclusions decreases due to the reaction between the inclusions and molten steel. Due to the good wettability between liquid CAMS inclusions and molten steel, large-size CAMS inclusions have clear heritability and remain in hot-rolled bars.

(3) The main optimization processes included canceling the addition of low-basicity slag, adding synthetic slag while BOF tapping, controlling slag basicity in the range of 5–9, controlling Al_2O_3 composition in the range of 23 mass%–28 mass%, and controlling the blowing flow of argon-blowing station. After the optimization, the size and quantity of CAMS inclusions were significantly reduced during refining process. The cleanliness of hot-rolled bars was improved which shows that the large-size CAMS inclusions in hot-rolled bars were mainly from the slag entrapment during BOF tapping.

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