Prediction of Spatial Composition Distribution of Inclusions in the Continuous Casting Bloom of a Bearing Steel under Unsteady Casting

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The transformation of non-metallic inclusions in the first continuous casting bloom of a bearing steel was studied through industrial trials and theoretical calculations. The spatial composition distribution of inclusions in the continuous casting bloom was predicted using a comprehensive model coupling heat transfer, thermodynamics, kinetics and industrial parameters. The effect of cooling rate on the transformation of composition of inclusions was investigated. The total oxygen in the first bloom gradually decreased from 12 ppm at the cast start to 7 ppm at 10 m cast length, and this variety in the total oxygen resulted in the decrease of the Al_2O_3 content in inclusions from 70% at the casting start to 50% at 10 m cast length. The transformation of inclusions during the continuous casting occurred preferentially at the quarter thickness of the bloom and the reaction zone gradually moved from the subsurface to the center of the bloom. Isothermal transformation diagrams and continuous cooling transformation diagrams of inclusions were established to characterize the transformation kinetics of inclusions. Inclusions at the subsurface of the CC bloom transformed at the mold cooling zone in the actual cooling of the continuous casting bloom, while inclusions at the center transformed at the air-cooling zone. The transformation ratio of inclusions in the CC bloom was determined by the cooling rate and the transformation rate was dominated by the temperature.

KEY WORDS: prediction; composition distribution; inclusions; bearing steel; continuous casting bloom; kinetics; thermodynamics; total oxygen.

1. Introduction

The increasing demand for super properties of bearing steels requires a strict control of non-metallic inclusions in the steel.^{1–6)} Extensive studies have been performed to study the formation, evolution and transformation of inclusions in bearing steels during the steelmaking,⁷⁾ steel refining,^{8,9)} calcium treatment,¹⁰⁾ continuous casting¹¹⁾ and electroslag remelting,^{12,13)} as well as a few investigations on composition transition of inclusions during the cooling and solidification of the steel.^{14,15)} In recent years, the transient evolution of inclusions in steels has attracted much attention and kinetic models were developed to predict the variation in the composition of inclusions in the molten steel during refining process^{16–27)} and in the solid steel during heating process.^{26–32)} The spatial distribution of the amount and size of inclusions on the cross section of continuous casting

(CC) products was predicted by combing the fluid flow, heat transfer and solidification, collision and motion of inclusions in the steel.^{31,33–35)} The spatial distribution of the composition of inclusions in a heavy rail CC bloom was predicted by the current authors.³⁶⁾ However, the evaluation of the spatial distribution of the composition of inclusions in bearing steel CC products has been little reported, which is of importance for the precise control of inclusions in CC products.

In the current study, the transformation of non-metallic inclusions in CC blooms of a bearing steel was studied through industrial trials and thermodynamic calculation. The transition in the composition of inclusions at the cast start of the CC bloom was discussed and the spatial distribution of the composition of inclusions on the entire cross section of the CC bloom was predicted using a comprehensive model. The effect of cooling rate of the CC bloom on the transformation of inclusions was studied, and the time-temperature-transformation (TTT) diagram and the continuous cooling transformation (CCT) diagram for the

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transformation ratio in the composition of inclusions was drawn and discussed.

2. Industrial Trials and Analysis

The production route for the current bearing steel was Basic Oxygen Furnace (BOF)→Ladle Furnace (LF)→Vacuum Degassing (VD)→CC→Rolling. During the tapping of BOF, aluminum alloys were added into the molten steel for the precipitation deoxidation and SiFe alloys were added to the top slag for the diffusion deoxidation by which the dissolved oxygen was lowered to a ppm level and finally the total oxygen in the molten steel was lowered to approximately 5 ppm during steady casting period. The bloom had a 310 mm × 480 mm dimension and the casting speed was 0.51 m/min. The pouring temperature, liquidus and solidus of the steel were 1 753 K, 1 728 K and 1 602 K, respectively. The cooling segments of the caster was divided into 5 water cooling zone and an air-cooling zone, as illustrated in Fig. 1. The cooling type for zone 1N and 1IO was the water spray cooling while the mist spray cooling was used in other water-cooling regions, followed by air-cooling process. The length and water flow

Fig. 1. Cooling zones of the Continuous Casting. (Online version in color.)

Table 1. Parameters of cooling zones.

Spray zone	Length (m)	Water flow rate (L/min)
Mold	0.72	1 916
1IO	0.53	28.8
1N		16.8
2IO	1.52	19.2
2N		15.6
3ION	2.65	21.6
4ION	2.17	14.4
5ION	2.15	12

Note: N is the narrow face, I is the loose side and O is the fixed side of the wide face of the CC bloom

rate of each cooling zone are given in Table 1.

Five cylindrical and five cubic samples were taken at the same corner of the cast start region of the first CC bloom, as shown in Fig. 2. Inclusions were analyzed using an automated SEM/EDS on the shaded surface of each sample. The chemical composition of the bearing steel in the current study is listed in Table 2, where the content of total aluminum (T.Al), total magnesium (T.Mg), and total calcium (T.Ca) in the steel were analyzed using an inductively coupled plasma emission spectrometry (ICP) and the total oxygen (T.O) was analyzed using a Leco Oxygen and Nitrogen Analyzer. Other chemical compositions were analyzed using an industrial spark OES.

3. The Total Oxygen and Inclusions in CC Blooms

Figure 3 shows the T.O of steel samples of the first CC bloom. The T.O at the cast start of the CC bloom was as high as 12 ppm induced by the reoxidation during the opening pouring at cast start. Then, the T.O in the steel gradually decreased with the cast length and reached approximately 7 ppm at a 10 m cast length. The high T.O in the steel at the cast start bloom was mainly because of the unsteady casting state, which was reflected in the reoxidation of the molten steel. Since the CC tundish and mold were filled with air before casting, the molten steel seriously contacted and mixed with the air at cast start period, resulting in a serious reoxidation. With increase of the cast length, the casting

Fig. 2. Sampling locations in the first CC bloom.

Fig. 3. The T.O along the cast length of the first CC bloom.

Table 2. Chemical composition of the current bearing steel.

C (%)	Si (%)	Mn (%)	T.Al (ppm)	T.S (ppm)	T.Ca (ppm)	T.Mg (ppm)	T.O (ppm)
0.975	0.169	0.34	130	15	4	2	Varied

became steady and steady so that the total oxygen was decreased, as shown in Fig. 3. The T.O still went lower after 10 m cast length, implying an unsteady state casting still.

Inclusions in the CC bloom were mostly in a shape of nearly sphere, and Fig. 4 shows the three-dimension morphology of a typical inclusion, which was extracted using an electrolysis with non-aqueous solution. The inclusion was with a diameter of approximately 8 μm and composed of two interlaced phases. The phase in grey color was $\text{MgO}\cdot\text{Al}_2\text{O}_3$ spinel with a polyhedron shape, and another phase in white color was CaS in a smooth shape.

The mean diameter and average composition of inclu-

Fig. 4. The 3D morphology and composition of a typical inclusion in the CC bloom. (Online version in color.)

Fig. 5. Features of inclusions along the cast length of the first CC bloom: (a) Mean diameter, (b) Composition. (Online version in color.)

sions along the cast length of the first bloom are shown in Fig. 5. Inclusions became slightly larger along the cast length, approximately 1.5 μm in average. The composition of inclusions was $\text{CaO}\text{--}\text{MgO}\text{--}\text{Al}_2\text{O}_3\text{--}\text{CaS}$, and the content of Al_2O_3 in inclusions decreased sharply while CaO and CaS slightly increased with the cast length. Figures 3 and 5 show that as the T.O in the steel decreased, Al_2O_3 in inclusions decreased while CaO and CaS in inclusions increased.

4. Prediction Model for the Composition of Inclusions in the CC Bloom

To predict the composition of inclusions in the CC bloom during the cooling process in real-time, a comprehensive model was established, considering heat transfer, thermodynamics, kinetics and industrial parameters, as illustrated in Fig. 6. A heat transfer and solidification model was used to simulate the temperature of the CC bloom at different distance below the meniscus. By combining industrial parameters, such as cast speed, the temperature distribution on the entire cross section of the CC bloom at any particular time was obtained. The equilibrium composition of inclusions at various temperatures was calculated using the FactSage7.1³⁷⁾ thermodynamic software with databases of FactPS, FToxide, and FSstel. The kinetic resistance was taken into consideration through the diffusion of dissolved elements in the solid steel matrix.

4.1. Heat Transfer and Solidification of the CC Bloom

The thermal history of the CC bloom was simulated using a traditional heat transfer and solidification model developed by the current authors.^{35,38,39)} Figure 7 shows temperature contours at typical cross sections of the zone 1 (1.25 m of the cast length), zone 3 (5.42 m of the cast length), zone 5 (9.74 m of the cast length), and air-cooling zone (21.25 m of the cast length) of the CC bloom. The temperature of the CC bloom decreased with the distance from the meniscus, and the decrease in the center of the CC bloom was much lower than that on the bloom surface. The bloom was

Fig. 6. Schematic of the comprehensive model to predict the composition of inclusions in CC products. (Online version in color.)

completely solidified at 21.25 m below the meniscus. The cooling history at different locations on the cross section of the CC bloom was different from each other, which led to a unique transformation process of inclusions at each location, resulting in a discrepancy in the composition of inclusions.

4.2. Thermodynamic Model for the Transformation of Inclusions with Temperature

Phases and compositions transition of inclusions in bearing steels with different contents of the T.O during solidification and cooling were calculated. **Figure 8** shows the evolution of phases of inclusions from 1 873 K to 1 073 K. Inclusions were all liquid oxides at a high temperature and mostly composed of liquid Al_2O_3 , CaO , MgO , and SiO_2 . As the temperature decreased, the content of $\text{MgO} \cdot \text{Al}_2\text{O}_3$ gradually increased, while liquid inclusions gradually disappeared and then the solid CaS and $\text{CaO} \cdot \text{Al}_2\text{O}_3$ precipitated. With the temperature further decreased, $\text{CaO} \cdot \text{Al}_2\text{O}_3$ turned into $\text{CaO} \cdot 2\text{Al}_2\text{O}_3$, and subsequently, $\text{CaO} \cdot 2\text{Al}_2\text{O}_3$ was gradually replaced by $\text{CaO} \cdot 2\text{MgO} \cdot 8\text{Al}_2\text{O}_3$. When the temperature dropped further, liquid sulfides and a large amount of pure substance MnS precipitated out. The content of oxides changed little when the temperature was below 1 473 K.

Converting inclusion phases into simple compounds, **Fig.**

9 gives the equilibrium content of Al_2O_3 , MgO , CaO , SiO_2 and CaS in inclusions. As the temperature decreased from 1 873 K to 1 673 K, the mean content of CaO and SiO_2 in inclusions decreased significantly. Meanwhile, the content of Al_2O_3 , MgO , and CaS rose up and inclusions varied from $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot \text{MgO}$ into $\text{CaS} \cdot \text{Al}_2\text{O}_3 \cdot \text{MgO}$. Moreover, with the decrease of the T.O, the content of Al_2O_3 in inclusions decreased remarkably, while the content of MgO and CaS rose up significantly at low temperature. The CaO content at high temperature was decreased with the T.O, while at low temperature, the CaO content had a slight increase with the T.O. The SiO_2 was only stable at high temperature, and there was little SiO_2 at low temperature, which agreed with observed industrial results.

4.3. Kinetic Model for Variation of the Composition of Inclusions with Time and Cast Length

A kinetic model was established based on the diffusion of elements in the steel and the mechanism of the kinetics is illustrated in **Fig. 10**. The process of the transformation was divided into three steps: (1) The temperature around inclusions varied as the cooling of the CC bloom. (2) A new thermodynamic equilibrium replaced the original one, resulting in the concentration gradient between the interface and the

Fig. 7. Simulated temperature profiles on cross sections of the CC bloom (a) 1.25 m, (b) 5.42 m, (c) 9.74 m, and (d) 21.25 m below the meniscus. (Online version in color.)

Fig. 8. Calculated phases transition of inclusions in CC blooms during the solidification and cooling. (Online version in color.)

Fig. 9. Average composition of inclusions during the cooling process (a) Al_2O_3 , SiO_2 , CaS ; (b) MgO , CaO . (Online version in color.)

Table 3. Diffusivities of Ca, Al, Si, Mg, S, and O in liquid, δ , and γ steel (m^2/s).^{38–40)}

Element	Liquid	δ	γ
Ca	3.5×10^{-09}	$0.76 \times \exp(-224\,430/\text{RT})/10\,000$	$0.055 \times \exp(-249\,366/\text{RT})/10\,000$
Al	3.5×10^{-09}	$5.9 \times \exp(-241\,186/\text{RT})/10\,000$	$5.15 \times \exp(-245\,800/\text{RT})/10\,000$
Si	4.78×10^{-09}	$8.0 \times \exp(-248\,948/\text{RT})/10\,000$	$0.07 \times \exp(-243\,000/\text{RT})/10\,000$
Mg	3.5×10^{-09}	$0.76 \times \exp(-224\,430/\text{RT})/10\,000$	$0.055 \times \exp(-249\,366/\text{RT})/10\,000$
S	4.1×10^{-09}	$4.56 \times \exp(-214\,639/\text{RT})/10\,000$	$2.4 \times \exp(-223\,426/\text{RT})/10\,000$
O	2.7×10^{-09}	$0.0371 \times \exp(-96\,349/\text{RT})/10\,000$	$5.75 \times \exp(-168\,454/\text{RT})/10\,000$

Fig. 10. Schematic of the kinetic model. (Online version in color.)

steel matrix. (3) Elements of Ca, Al, Si, Mg, S, and O were transferred between the steel bulk and the steel-inclusion interface with a diffusion rate calculated using Eq. (1).

$$dn_i = N_{inc} \times \frac{D_i}{r} \times \frac{\rho_{steel}}{w_{steel}} \times A_{inc} \times (n_i^{bulk} - n_i^{interface}) \times dt \dots (1)$$

where n_i is the molar quantity of element i (Al, Si, Mg, Ca, S, or O) in the steel matrix, mol; N_{inc} is the amount of inclusions; D_i is the diffusivity of element i , m^2/s , as listed in Table 3;^{38–40)} r is the radius of the inclusion, m; ρ_{steel} is the density of the steel, kg/m^3 ; w_{steel} is the weight of steel, kg; A_{inc} is the area of interface, m^2 ; dt is the time interval, s. The superscript *bulk* means the steel matrix, and *interface* means the steel-inclusion interface.

In the current kinetic model, the diffusion of elements between the steel matrix and inclusions was considered to be the rate-control step and chemical reactions were always in equilibrium at the inclusion-steel interface. Inclusions were assumed to be spherical with a diameter of $1.5 \mu\text{m}$, which was the measured average diameter of inclusions in Fig. 5(a). The composition of the steel matrix and inclusions matrix were simply assumed to be uniform.

4.4. Variation of the Composition of Inclusions along Cast Length of the CC Bloom

The measured and predicted composition of inclusions in the first CC bloom are shown in Fig. 11. The experimental data was reproduced well by the kinetic model while it was in a large discrepancy with the thermodynamic equilibrium calculation. Thus, the thermodynamic calculation was unable to accurately predict the composition of inclusions in the CC bloom. The kinetic feature of this transformation due to the diffusion of elements in the solid steel determined its less transition than the pure thermodynamic calculations.

4.5. Variation of the Composition of Inclusions on the Entire Cross Section of the CC Bloom

The thermal history at different positions of the CC bloom

Fig. 11. Comparison of the measured and the predicted composition of inclusions in the first CC bloom along cast length. (Online version in color.)

was quite different, which inevitably led to the diversity in the composition distribution on the cross section of the CC bloom. Hence, to understand the composition evolution of inclusions on the entire cross section of the first CC bloom, the variation of inclusions composition on the cross section at different times, namely at different cast length, was simulated and are shown in Fig. 12. Effects of segregation and micro-segregation were not included in the simulation, as segregation elements C and S had little effects on the transformation of inclusions. Carbon didn't participate in the transformation where the main reaction was changing from CaO into CaS. The little effect of sulfur on the transformation was due to the quite higher content of sulfur than calcium in the bearing steel. Therefore, even if there was some segregation of sulfur, its effects might be negligible. For another word, the model for accurately predicting the center segregation or the micro-segregation was quite complex. To simplify the current model, the center segregation or the micro-segregation were not considered in the current study. The CaS content in inclusions rose up obviously with the solidification of the steel while the CaO content had a decrease tendency. The reaction zone for the transformation gradually moved from the surface to the center of the CC bloom, and transformation reactions tended to occur preferentially at a quarter thickness of the bloom due to the condition of the rapid cooling and little diffusion of dissolved elements at bloom subsurfaces. Meanwhile, the temperature at the bloom center was so high that thermodynamically transformation was hard to occur. Only the region at the quarter thickness of the bloom had the moderate temperature, guaranteeing both thermodynamic condition and kinetic condition for the transformation reactions. In

Fig. 12. Calculated composition profiles of inclusions on the cross section of the bloom with T.O of 7 ppm (a) 9.74 m, and (b) 21.25 m below the meniscus. (Online version in color.)

Fig. 13. Calculated composition profiles of inclusions on the cross section of the bloom of cast end with T.O of 10.8 ppm. (Online version in color.)

the bloom of cast end, the composition of inclusions in the interior of the bloom became more uniform.

The effect of the T.O content of the steel on the composition transformation of inclusions are shown in **Fig. 13**, where the T.O of the steel was 10.8 ppm. The composition transformation process of inclusions was similar to that of the bloom with 7 ppm T.O. The difference was the ingredient content of inclusions in the bloom at cast end. More T.O in steel increased the content of Al_2O_3 and reduced the content of CaS in inclusions in the bloom of cast end. In the bloom of cast end with 7 ppm T.O, contents of Al_2O_3 and CaS in inclusions on the entire cross section were approximately 46% and 35%, respectively, while that in the bloom at cast end with 10.8 ppm T.O were 61% and 20%, respectively. Thus, low T.O in steel was beneficial to reduce

contents of Al_2O_3 and CaO in inclusions in steel CC blooms.

5. Isothermal Transformation and Continuous Cooling Transformation in the Composition of Inclusions in the CC Bloom

It is widely recognized that the cooling rate plays a critical role in the microstructure of the CC bloom, and TTT and CCT curves are employed to describe this phenomenon. In the current study, TTT and CCT curves were utilized to the transformation in the composition of inclusions during steel cooling process. For the current steel, the main reaction occurred during steel cooling was the transformation of CaO into CaS and the transformation ratio of the reaction was defined as follows:

$$\alpha_t = \frac{(\text{CaS})_t}{(\text{CaS})_{\text{equ}}} \times 100\% \quad (2)$$

where $(\text{CaS})_t$ is the content of CaS in inclusions at time of t ; $(\text{CaS})_{\text{equ}}$ is the equilibrium content of CaS in inclusions calculated using FactSage.

In the current section, the transformation in the composition of inclusions with diameter of $3 \mu\text{m}$ in the steel with a 7 ppm T.O and other composition listed in Table 2 was investigated. The initial composition of inclusions used in the calculation was set to be the thermodynamic equilibrium composition of inclusions at 1 753 K, which was the pouring temperature of the continuous casting. The initial composition of inclusions was 33.64% Al_2O_3 -24.56%MgO-0.05%CaS-38.71%CaO-3.04% SiO_2 in mass fraction.

5.1. Isothermal Transformation (Time, Temperature, Transformation, TTT)

Figure 14 shows the transformation ratio of inclusions in the steel at 1 203 K–1 623 K with 10 discrete intervals. It took a shorter time for the inclusion in the steel to reach a fixed transformation ratio at a higher temperature. The time for a complete transformation at 1 623 K was nearly 5 000 seconds, while that at 1 223 K was almost 1 million seconds. Thus, the temperature was the decisive factor for the transformation.

A contour of the TTT diagram was used to quantitatively evaluate the transformation ratio, as shown in **Fig. 15**. There was no transformation in the composition of inclusions when the temperature was higher than 1 700 K, which was consistent with the thermodynamic analysis. When the temperature was lower than 1 700 K, the transformation ratio increased with the reaction time, and the transition at a lower temperature significantly lag behind than that at a higher temperature. Figure 15 can be used to precisely control the composition of inclusions in the CC bloom during the heating and holding at a constant temperature. For example, once the target content of CaS in inclusions is given, the holding time of the CC bloom at a fixed temperature can be obtained. If the 1% transformation ratio was defined as the start of the transformation and the 97% conversion ratio as the complete one, the entire zone was divided into 5 typical sub-zones named by “No transformation”, “Incomplete transformation”, and “Complete transformation”, as shown in **Fig. 16**. No transformation in Zone 1 and incomplete transformation in Zone 3 were induced by the thermody-

Fig. 14. Calculated isothermal transformation in the composition of inclusions in the steel with time. (Online version in color.)

Fig. 15. TTT diagram for the composition transformation of inclusions in the steel. (Online version in color.)

Fig. 16. Isothermal partition diagram for the composition transformation of inclusions in the steel. (Online version in color.)

dynamic restriction, while Zone 2 and Zone 4 were dominated by the kinetic restriction.

5.2. Continuous Cooling Transformation (CCT) with a Fixed Cooling Rate

The cooling rate of the CC bloom varied with the casting time and the position of the entire cross section. To clearly show the effect of the cooling rate on the transformation of inclusions in the steel, it was simply assumed a fixed cooling rate during the cooling of the steel and the CCT in the composition of inclusions in steel under the simple cooling condition was calculated. The start temperature was set as 1753 K, which implied a 25 K superheat for the current steel. Thirteen cooling rates, as listed in **Table 4**, were employed to study the dependency of the final composition of inclusions in the cooled steel on the cooling rate. As shown in **Fig. 17**, the content of CaO and CaS in inclusions was dominated by the cooling rate, while the content of Al_2O_3 , MgO, and SiO_2 in inclusions depended little on the cooling rate if the cooling rate was larger than 1 K/s. Thus, the components of Al_2O_3 , MgO, and SiO_2 in inclusions participated little in the transformation reactions during the cooling process of the steel. The transformation occurred little when the cooling rate was high since there was no enough time for the transfer of reactants. When the cooling rate was lower than approximately 2 K/s, the transformation reaction occurred rapidly, and as a result, the content of CaS in inclusions increased sharply as the cooling rate decreased. With the cooling rate lower than 0.05 K/s, the transformation reaction could be completed. The cooling rate of 2 K/s could be defined as a turning point. When the cooling rate was higher than 2 K/s, the composition of inclusions changed little during the cooling process, which was at the similar situation to the loose and fixed sides of the CC bloom. While the cooling rate was lower than the turn-

Table 4. Cases with different cooling rates.

Cases	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C_R (K/s)	15	10	6	3	2	1	0.7	0.5	0.4	0.2	0.1	0.05	0.03

Fig. 17. Composition of inclusions in the CC bloom with different cooling rates. (Online version in color.)

ing point, CaO transferred into CaS, and the transformation ratio increased with the decrease of the cooling rate, which corresponded to the situation inside the CC bloom.

As the components of Al_2O_3 , MgO , and SiO_2 in inclusions hardly participated in transformation reactions during the cooling process of the steel, the α defined in Eq. (2) was used to evaluate the degree of the transformation. **Figure 18** shows the regressed relation between the transformation ratio and the cooling rate as in Eq. (3).

$$\alpha = 1.67 + 90.37e^{\frac{C_R}{0.35}} + 18.64e^{\frac{C_R}{2.70}} \dots\dots\dots (3)$$

where α is the transformation ratio, %; C_R is the cooling rate, K/s.

Like the TTT diagram, a contour of the CCT diagram was also calculated to visualize the transformation process, as shown in **Fig. 19**. The abrupt transformation occurred at the high temperature region, implying that the holding time at the high temperature played a key role in the transformation. There were two critical cooling rates for the transformation.

Fig. 18. The dependency of transformation ratio of the composition of inclusions in the CC bloom on the cooling rate. (Online version in color.)

Fig. 19. The CCT diagram for the composition transformation of inclusions in the steel. (Online version in color.)

One was for the start transformation, and another was for the complete transformation. When the cooling rate was higher than 24.7 K/s, the composition of inclusions varied little with time. While the cooling rate was lower than 0.067 K/s, the transformation was nearly completed. **Figure 19** can be used to design the cooling system for the target composition of inclusions. For example, if no-CaO inclusions are required in the steel, according to **Fig. 19**, the cooling rate needs to be lower than 0.0067 K/s.

According to **Fig. 19**, the entire region was also divided into 5 zones, as shown in **Fig. 20**. The definition of each zone was the same as **Fig. 16**. **Figure 20** is a simplified version of **Fig. 19**, which can be used to quickly judge whether the transformation has occurred or completed once a cooling rate is given.

5.3. Actual Cooling Transformation (ACT)

Five positions with the same interval distance from the loose side to the center of the CC bloom were chosen to evaluate the transformation in the composition of inclusions during the actual cooling process of the steel bloom. The cooling rate was calculated as negative time derivative of temperature based on **Fig. 7**, as shown in **Fig. 21**. The maximum cooling rate of the point P1 was as big as 10 K/s, which was quite higher than other points. The major cooling area of P1, which were located near the loose side, was the continuous casting mold zone, while that of P2 were the mist spray cooling zones of zone 2 and zone 3. The cooling of P4 and P5, which were near the center of the CC bloom, occurred mainly during air-cooling.

Using the thermal history of the 5 positions, the composition transformation ratio and transformation rate defined as Eq. (4) of inclusions were calculated, as shown in **Figs. 22** and **23**, respectively. The transformation ratio of inclusions at position P3, which located at the quarter thickness of the CC bloom, was the highest, while inclusions at P1 had little transformation in composition during the cooling process. The distribution of maximum transformation rate of inclusions varied with the spatial position and gradually moved from the mold zone to the air-cooling zone. The composi-

Fig. 20. The CCT partition diagram for the composition transformation of inclusions in the steel. (Online version in color.)

Fig. 21. Calculated cooling rate at 5 positions with the interval distance from the loose side to the center of the CC bloom. (Online version in color.)

Fig. 22. Calculated transformation ratio of inclusions at 5 positions from the loose side to the center of the CC bloom. (Online version in color.)

Fig. 23. Calculated transformation rate of inclusions at 5 positions from the loose side to the center of the CC bloom. (Online version in color.)

Fig. 24. The transformation rate of the composition of inclusions at 5 positions with 17.5 m, 20 m, and 25 m below the meniscus. (Online version in color.)

tion of inclusions at the loose side was transformed only at the mold zone, while those close to the center of the bloom was transformed only at the air-cooling zone. The composition transformation of inclusions at position P3 started from the spray cooling zone of zone 3, which was the best condition for the transformation.

$$T_R = \frac{d\alpha_i}{dt} \dots\dots\dots (4)$$

where, T_R is transformation rate, %/s.

Comparing Figs. 21, 22 and 23, it was found that the correlation between the transformation rate and the cooling rate was not obvious, and the maximum T_R occurred at the same temperature of approximately 1 700 K, which is the initial transformation temperature of CaO into CaS. The T_R had a strong correlation with the temperature. **Figure 24** shows the T_R at 5 positions from the loose side to the center of the CC bloom with three cast length from the meniscus. The value of T_R increased with the temperature, implying that inclusions at the higher temperature locations in the steel had a faster transformation under the condition that the temperature should be lower than the initial transformation temperature of CaS. If the large transformation ratio of inclusions was required, the longer residence time at high temperature below the initial transformation temperature of CaS was the better. Thus, the transformation ratio was determined by the cooling rate and the transformation rate was dominated by the temperature.

6. Conclusions

The composition distribution of inclusions in the first CC bloom of a bearing steel was investigated, and a comprehensive model coupling industrial parameters, heat transfer of the CC bloom, thermodynamics, and kinetics was established to predict the distribution of the composition of inclusions at the entire cross section of the CC bloom. The following conclusions were derived.

(1) The content of T.O in steel samples decreased gradually from 12 ppm at the cast start to 7 ppm at 10 m

cast length. This variety of the T.O resulted in the varied composition of inclusions along the cast length of the CC bloom. The content of Al_2O_3 in inclusions decreased from 70% at casting start to 50% at 10 m cast length, while CaO and CaS had a little increase.

(2) During the CC process, transformation reactions tended to occur preferentially at the quarter thickness of the continuous casting bloom as proper conditions of both thermodynamics and kinetics.

(3) The composition of inclusions in the final bloom was generally uniform on the cross section, except for the subsurface region. In the final bloom with 7 ppm T.O, contents of Al_2O_3 and CaS in inclusions on the entire cross section were approximately 46% and 35%, respectively, while that at the cast end of the bloom with 10.8 ppm T.O were 61% and 20%, respectively.

(4) The cooling rate had a notable effect on the transformation of inclusions. The cooling rate of 2 K/s was a turning point for a significant transformation of the composition of inclusions. The transformation ratio was an exponential function with the cooling rate:

$$\alpha = 1.67 + 90.37e^{\frac{C_R}{0.35}} + 18.64e^{\frac{C_R}{2.70}}.$$

(5) The TTT diagram and CCT diagram of inclusions were calculated, which could be used to precisely control the composition of inclusions in the CC bloom during the cooling process.

(6) Inclusions at the subsurface of the CC bloom transformed at the mold cooling zone, while inclusions at the center transformed at the air-cooling zone. The maximum transformation rate corresponded to the initial transformation temperature of CaS, independent of the position.

(7) The transformation ratio of inclusions in the CC bloom was determined by the cooling rate and the transformation rate was dominated by the temperature. The cooling rate at a high temperature below the initial transformation temperature of CaS roughly reflected the entire transformation progress.

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