Composition Change of Inclusions in High Carbon Steel before and after Addition of Aluminum

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(Received on July 31, 2020; accepted on November 4, 2020; originally published in Tetsu-to-Hagané, Vol. 105, 2019, No. 11, pp. 1042–1049)

The effect of Al addition at the midpoint of the metal-slag reaction on the formation of MgO·Al\(_2\)O\(_3\) spinel-type inclusions was investigated by laboratory-scale experiments and a kinetic model calculation with the aim of reducing spinel-type inclusions in high-carbon steel. As results of the experiments, the total Mg content in the steel and the average content of MgO in the inclusions were relatively low before Al addition, and formation of spinel-type inclusions was rare. After Al addition, spinel-type inclusions formed when CaO/SiO\(_2\) and CaO/Al\(_2\)O\(_3\) in the slag were high, and the total Mg content in the steel and the average MgO content in the inclusions were also high. On the other hand, formation of spinel-type inclusions was suppressed at lower CaO/SiO\(_2\) and CaO/Al\(_2\)O\(_3\) in the slag. Therefore, the experimental results indicated that Al addition at the midpoint of the reaction and control of the slag composition are effective for suppression of spinel-type inclusions. However, spinel-type inclusions formed soon after Al addition in slag with higher CaO/SiO\(_2\) and higher CaO/Al\(_2\)O\(_3\). To evaluate the effect of midpoint addition of Al in the actual process, a kinetic model calculation was carried out. According to the calculation, the increase in the Mg content in the steel under actual-scale conditions was lower than that in the laboratory, and formation of spinel-type inclusions could be avoided.

KEY WORDS: high carbon steel; inclusion; spinel; Al addition; slag composition.

1. Introduction

It is desirable to control the composition and morphology of non-metallic inclusions in steel materials, or to reduce their total amount, since these inclusions have an adverse effect on material quality and operation. For example, MgO·Al\(_2\)O\(_3\) spinel-type inclusions have been observed at the origin of cracks in high carbon steels such as bearing steels in which fatigue resistance is required. Therefore, it is considered necessary to control spinel-type inclusions in order to further improve fatigue life.

According to previous research, spinel-type inclusions are considered to be formed by the reaction of Mg, which is generated by the reaction of Al in molten steel and MgO in the slag or refractory, with Al\(_2\)O\(_3\) inclusions, which are deoxidation products, as shown in the following reactions (1) and (2).

\[
3(MgO) + 2[Al] = 3[Mg] + (Al_2O_3) \quad \text{............ (1)} \\
3[Mg] + 4Al_2O_3 = 3MgO \cdot Al_2O_3 + 2[Al] \quad \text{........ (2)}
\]

In particular, the slag composition has a significant influence on the formation of spinel-type inclusions. As the MgO activity in the slag decreases due to the decrease in the CaO/SiO\(_2\), CaO/Al\(_2\)O\(_3\) or MgO content in the slag, Mg formation in the molten steel and spinel-type inclusions tend to be suppressed under these conditions. However, in secondary refining processes such as the ladle furnace (LF), the MgO in the refractory dissolves into the slag as treatment proceeds. Since this increases the MgO activity in the slag, it is difficult to suppress the formation of spinel-type inclusions simply by reducing CaO/SiO\(_2\) and CaO/Al\(_2\)O\(_3\) in the slag.

Therefore, the possibility of suppressing spinel-type inclusion formation was investigated from other viewpoints in addition to control by the slag composition. As described above, in order to suppress spinel-type inclusions, it is important to suppress Mg formation from the slag. Reduction of the MgO activity in the slag is discussed above, but according to reaction (1), in equilibrium theory, reducing the Al content in the molten steel is also effective for suppressing spinel-type inclusions. However, this approach is not practical, as Al is used as a deoxidizing material in order to reduce oxygen in the steel. On the other hand, there is a possibility that the reaction with MgO in the slag can be shortened and MgO reduction can be suppressed by delay-
In order to stir the molten steel, Ar gas was blown at a flow rate of 2 Nl/min from a porous plug installed at the bottom of the crucible. After adjusting the molten steel composition, the metal was sampled and 2 kg of flux was added onto the molten steel. In this experiment, the flux addition timing was 0 min, i.e., at the start of the reaction. As shown in Table 2, the four kinds of fluxes A to D, which were the mixtures of reagents, were used to investigate the effect of the slag composition. Flux A had the highest CaO/SiO2 and CaO/Al2O3, whereas flux B and C were used as lower CaO/SiO2 and CaO/Al2O3 fluxes, and flux D was used as the lowest CaO/SiO2 and CaO/Al2O3 flux. The MgO crucible was used for fluxes A, B and C, and an Al2O3 crucible was used for flux D to decrease the CaO/Al2O3 in the slag while suppressing the increase in the MgO content of the slag. Therefore, in the case of flux D, melting from the crucible into the slag was large, and the component fluctuation of the slag was relatively large compared to that with fluxes A to C. When using fluxes A to C with the MgO crucible, since the saturation solubility of MgO is lower than that of Al2O3, dissolution from the crucible into the slag is considered smaller than that with flux D, and the variation of slag components is small. Metal samples were collected at a predetermined time after flux addition. Further, about 0.04 mass% of metallic Al was added to the molten steel 30 min after flux addition, and deoxidation was carried out. Thereafter, samples of the metal and slag were taken at a predetermined time, and the experiment was terminated about 20 min after Al addition. During the experiment, the temperature and oxygen activity in the molten steel were measured as appropriate. The collected samples were analyzed for each component in the metal and slag by ICP-AES/MS. The inclusions in the metal samples were also evaluated using SEM-EDX (Aspex Explore) with an automatic inclusion measurement system.

3. Experimental Results

3.1. Changes in Molten Steel Composition

The changes in the Al and total Mg (hereinafter, T.Mg) contents in the molten steel are shown in Figs. 1 and 2. In the case of fluxes A to C, the Al content in the molten steel increased gradually after flux addition. It is considered that the reduction of Al2O3 in the slag was caused by Si in the

| Flux | CaO | SiO2 | Al2O3 | MgO | C/S* | C/A* | Crucible Target |
|------|-----|------|-------|-----|------|------|-----------------|
| A    | Before 56 7 22 5 | 8.0 2.5 | MgO | High-C/S |
| A    | After 55 8 24 6 | 6.7 2.3 | MgO | High-C/A |
| B    | Before 50 14 21 5 | 3.6 2.3 | MgO | Mid-C/S |
| B    | After 49 13 23 7 | 3.9 2.2 | MgO | High-C/A |
| C    | Before 44 11 30 5 | 4.0 1.5 | MgO | Mid-C/S |
| C    | After 42 9 31 8 | 4.5 1.4 | MgO | Mid-C/A |
| D    | Before 47 12 26 5 | 4.0 1.8 | Al2O3 | Low-C/S |
| D    | After 35 10 43 5 | 3.5 0.8 | Al2O3 | Low-C/A |

*) C/S = CaO/SiO2, C/A = CaO/Al2O3

Table 1. Composition of molten steel used in experiment.

| C  | Si  | Mn  | S   | Cr  | (mass%) |
|----|-----|-----|-----|-----|---------|
| 1.0| 0.2 | 0.35| 0.004| 1.5  |         |

Table 2. Composition of flux and slag before and after experiment (mass%).
On the other hand, in the case of flux D, the Al content in the molten steel decreased gradually after flux addition. After Al addition, the Al content in the molten steel increased to around 0.035 mass% in all cases, and then decreased with time. The content of T.Mg in the steel was around 1 mass ppm before the addition of fluxes A to C. In the case of flux D, the Al content in the molten steel was about 0.01 mass% before flux addition, which was higher than that when using the other fluxes, but the T.Mg content in the molten steel was 0.1 mass ppm, which was lower than the other levels. In other words, the reaction between the metal and refractory occurred before flux addition, and
in the case of fluxes A to C, Mg was formed in the molten steel due to the use of the MgO crucible, while in the case of flux D, Al was formed in the molten steel due to the use of the Al₂O₃ crucible. The content of T.Mg in the molten steel in this study is defined as the sum of the content of Mg dissolved in the steel and the content of Mg in the inclusions. About 25 min after flux addition, the change in the T.Mg content in the molten steel displayed different behaviors with each flux. That is, the T.Mg content was 2.6 mass ppm in the case of flux A (highest CaO/SiO₂ and CaO/Al₂O₃), but was only 0.5 mass ppm with flux D (lowest CaO/SiO₂ and CaO/Al₂O₃). After Al addition, the content of T.Mg in the molten steel increased further for all fluxes, to around 5 mass ppm for flux A and to around 3 mass ppm for fluxes B and C. Although T.Mg increased with flux D, the final content was limited to about 0.6 mass ppm. These results indicate that the content of T.Mg in the molten steel increases without Al deoxidation and is affected by the flux composition. Therefore, as the CaO/SiO₂ and CaO/Al₂O₃ in the slag increased, the T.Mg content in the molten steel also increased. Furthermore, this tendency became more remarkable after Al addition.

3.2. Composition Change of Inclusions in Steel

Figure 3 shows the average composition change of the inclusions in the steel when each flux was used. In this study, the average composition of the inclusions in the steel is the average of the measured composition of oxide inclusions. Before Al addition, the inclusions were mainly Al₂O₃–SiO₂–MnO type inclusions, and with increasing time, the content of Al₂O₃ in the inclusions increased and approached the Al₂O₃ type. After Al addition, the MgO content in the inclusions increased and the inclusions changed to the Al₂O₃–MgO type. In the case of flux A, the main inclusions were MgO·Al₂O₃ spinel-type and the MgO content in the inclusions was high. In the case of fluxes B and C, the inclusions changed to Al₂O₃ and spinel-type inclusions after Al addition. In the case of flux D, although the inclusions changed to the Al₂O₃ type after Al addition, the MgO content in the inclusions remained low, and the formation of spinel-type inclusions was less than in the case of other fluxes. The change in the average MgO content in the inclusions is shown in Fig. 4. In all the fluxes, the average content of MgO in the inclusions was less than 10 mass% before Al addition. In the case of fluxes A, B and C, the average content of MgO in the inclusions increased rapidly to more than 20 mass% at 3 min after Al addition. In the case of flux D, the average MgO content in the inclusions also increased after Al addition, but nevertheless remained less than 10 mass%. The relationship between the T.Mg content in the steel and the average MgO content in the inclusions is shown in Fig. 5. Both before and after Al addition, as the T.Mg content in the steel decreased, the average MgO content in the inclusions also decreased. Here, before Al addition, the T.Mg content in the steel was 1.9 mass ppm 25 min after the addition of flux C, whereas the average MgO content in the inclusions was 3.5 mass%, which was lower than the relationship obtained from other results. This is considered to be because the molten steel was reoxidized by disturbance during the experiment, and the MgO content in the inclusions showed a relative decrease owing to the generated inclusions. The relationship between the T.Mg content in the steel, the average MgO content in...
As the CaO/SiO$_2$ and CaO/Al$_2$O$_3$ in the slag decreased, the T.Mg content in the steel and the average MgO content in the inclusions decreased because the MgO activity in the slag was lower and the oxygen activity at the metal-slag interface was higher with the decrease in the CaO/SiO$_2$ and CaO/Al$_2$O$_3$ in the slag. This tendency was more remarkable after Al addition, and the increase in the T.Mg content in the steel and the MgO content in the inclusions after Al addition was smaller as the CaO/SiO$_2$ and CaO/Al$_2$O$_3$ decreased. These results indicate that the slag composition affects the T.Mg content in steel and the MgO content in the inclusions both with and without Al addition. Jiang et al. conducted equilibrium experiments with slag in the relatively low Al concentration range ($\leq$0.01 mass%) of medium carbon steel. Although there are differences in the experimental system and the composition of molten steel, the lower the CaO/SiO$_2$ in the slag, the lower the Mg content in the molten steel and the MgO content in the inclusions. This tendency is similar to the experimental results of this study for high-carbon steel. In other words, the changes in the Mg content in the molten steel and the MgO content in the inclusions before and after Al addition obtained in this experiments can occur not only in high carbon steel but also in other component systems.

As described above, the inclusion composition history before Al addition becomes apparent after Al addition. That is, as in the case of the flux A, when the MgO content in the inclusions was relatively high before Al addition, the inclusions were changed to spinel-type inclusions immediately after Al addition. On the other hand, when the MgO content in the inclusions was low before Al addition as in the case of flux D, the MgO content was kept low even after Al addition, and the formation of spinel-type inclusions hardly occurred. Therefore, it is important not only to delay the Al addition time but also to control the inclusion composition by controlling the slag composition even before Al addition for the reduction of spinel-type inclusions.

Fig. 6. Relationship between total Mg content in steel, average MgO content in inclusions and slag composition before and after Al addition.
4. Discussion

4.1. Thermodynamic Study of Inclusion Composition

In order to investigate the inclusion composition obtained in this experiment, thermodynamically stable inclusions were evaluated from the steel compositions. Here, a phase stability diagram of the inclusions was prepared at the molten steel temperature of 1 863 K in the experiment, considering silicate, Al₂O₃, MgO·Al₂O₃, and MgO as the generated phases. The boundaries of each phase were calculated from the equilibrium constants (7) to (11) for reaction Eqs. (2) to (6). In this study, the equilibrium constants (7) to (11) were calculated using the equilibrium constants shown in Table 3. The steel components shown in Table 1 were used in the calculations. For the sake of simplicity, only the first-order interaction coefficient shown in Table 4 was considered for the activity coefficient of each component in the steel. The oxide was basically regarded as a pure substance, and the activity of the oxide was unity. Since MgO·Al₂O₃ is a solid solution, the activities in the reaction were set to 0.47 and 0.81, respectively. Then, in the calculation of the reaction Eqs. (4), (5) and (6), the SiO₂ activity was calculated using three kinds of substance, and the activity of the oxide was unity. Since MgO·Al₂O₃ is a solid solution, the activities in the reaction were set to 0.47 and 0.81, respectively.

In the case of fluxes A, B and C, the experimental results were located in the silicate stable region or near the boundary between silicate and MgO·Al₂O₃ in the initial stage and before Al addition. After Al addition, the results moved to the MgO·Al₂O₃ stable region. In the case of flux D, the results were located near the boundary between silicate and Al₂O₃ or MgO·Al₂O₃ in the initial stage and before Al addition, and then moved to near the boundary between Al₂O₃ and MgO·Al₂O₃ after Al addition. Since the Mg content here is the T.Mg content in the steel, as mentioned above, and the dissolved Mg content in the steel is estimated to be located below these plots, the observed inclusion composition and the inclusion composition predicted from the phase

\[
2\text{Al}_2\text{O}_3 + 3[\text{Si}] = 3\text{SiO}_2 + 4\text{[Al]} \quad \quad \quad \quad (5)
\]
\[
\text{MgO} - \text{Al}_2\text{O}_3 + 2[\text{Si}] = 2\text{SiO}_2 + [\text{Mg}] + 2[\text{Al}] \quad \quad \quad \quad (6)
\]
\[
\log K(2) = 26.92 - 27940/T \quad \quad \quad \quad \quad \quad \quad (7)
\]
\[
\log K(3) = -23.64 + 32285/T \quad \quad \quad \quad \quad \quad \quad (8)
\]
\[
\log K(4) = -19.96 + 20710/T \quad \quad \quad \quad \quad \quad \quad (9)
\]
\[
\log K(5) = -10.96 + 270/T \quad \quad \quad \quad \quad \quad \quad (10)
\]
\[
\log K(6) = -16.28 + 9133/T \quad \quad \quad \quad \quad \quad \quad (11)
\]

where \(K(2)\) to \(K(6)\) are the equilibrium constants of reactions (2) to (6), and \(T\) is the molten steel temperature (K).

The inclusion phase stability diagram obtained by the above calculation is shown in Fig. 7, which also shows the results obtained in this experiment. For a strict analysis, the content of dissolved Mg in the steel should be compared with the phase stability diagram. However, since the actual values were not clear, the comparison was carried out using the T.Mg content in the steel.

Table 3. Equilibrium constants used to calculate equilibrium constants of reactions (2) to (6).

| Reactions | log \(K\) | References |
|-----------|-----------|------------|
| \(\text{Al}_2\text{O}_3 = 2[\text{Al}] + 3[\text{O}]\) | \(-4.28 \pm 4700/T\) | (10) |
| \(\text{MgO} = [\text{Mg}] + [\text{O}]\) | \(-4.28 \pm 4700/T\) | (11) |
| \(\text{SiO}_2 = [\text{Si}] + 2[\text{O}]\) | \(-4.28 \pm 4700/T\) | (12) |
| \(\text{MgO} \cdot \text{Al}_2\text{O}_3 = \text{MgO} + \text{Al}_2\text{O}_3\) | \(-4.28 \pm 4700/T\) | (13) |

Table 4. First-order interaction coefficients \((c')\) used in this study (All data without notation are from reference No. 13).

| \(i\) | \(j\) | C | Si | Mn | Al | Cr | Mg | O |
|------|------|---|----|----|----|----|----|----|
| Si   | 0.18 | 0.103 | -0.00146 | 0.058 | -0.0003 | - | 0.119 |
| Al   | 0.091 | 0.056 | -0.004 | 0.043 | 0.0006 | 0.13 | 0.2 | -0.011 |
| Mg   | -0.31 | -0.096 | -0.017 | 0.01 | -432 | 0.013 | - |
stability diagram may actually show a closer tendency. For the final inclusion composition, good correspondence can generally be seen between the results of this experiment and the phase stability diagram.

### 4.2. Actual-scale Kinetic Study

According to the results of this experiment, although the MgO content in the inclusions remained relatively low before Al addition, the MgO content in the inclusions increased greatly immediately after Al addition, except in the case of flux D, and the formation of spinel-type inclusions was very fast. However, under actual-scale conditions, the amount of molten steel relative to the metal-slag reaction interfacial area is large, and the effect of delaying Al addition, that is, suppression of the Mg content in the steel and the MgO content in the inclusions, is expected.

Therefore, the change of the Mg content in the steel was estimated by a calculation of the metal-slag reaction at the actual scale. The kinetic model reported by Harada et al.\(^\text{17}\) was used for the calculation. The calculation conditions are shown in Table 5. The molten steel and flux compositions were the same as in the laboratory experiment, and only the amounts of molten steel and flux and the flow rate of the stirring gas were scaled up. The parameters used in the model were the same as those in the previous report.\(^\text{31}\) The stirring gas flow rate was determined so that the stirring energy density in the laboratory experiment and the calculation for the actual operation would be the same. In the calculation, as in the laboratory experiment, 0.04 mass% of Al was added to the molten steel 30 min after the metal-slag reaction started.

First, the calculations were carried out based on the conditions of the laboratory experiment, and the calculation results were compared with the experimental results. The results of the comparison between the T.Mg content in the steel and the average MgO content in the inclusions for flux A are shown in Fig. 8. The calculated results roughly corresponded to the experimental results. Figure 9 shows the calculated changes in the Mg and Al contents in the steel with fluxes A to D superimposed on the inclusion phase stability diagram prepared in section 4.1. Compared with the experimental results, the calculated values of the dissolved Mg content in the steel showed a tendency closer to the actual inclusion composition. As these results confirmed that the experimental results could be reproduced by this model, the calculation was carried out under the actual-scale conditions shown in Table 3. Figure 10 shows the calculation results under the actual-scale conditions assuming use of flux A. The model calculation results were described in the inclusion phase stability diagram prepared in section 4.1 and compared with those under the

| Table 5. Basic conditions for laboratory- and actual-scale calculation. |
|---------------------------------------------------------------|
| Laboratory-scale                                             | Actual-scale |
| Weight of molten steel (kg)                                  | 30           | 200 000       |
| Weight of slag (kg)                                          | 2            | 2 000         |
| Ar stirring gas flow rate (NL/min)                           | 2            | 1 500         |
| Bath diameter (m)                                            | 0.18         | 3             |

Fig. 8. Calculation results of change in total Mg content in steel and average MgO content in inclusions compared with experimental results for flux A.

Fig. 9. Calculation results of change in soluble Mg and Al contents in molten steel under laboratory-scale conditions for fluxes A, B, C and D. (Online version in color.)

Fig. 10. Calculation results of change in Mg and Al contents in molten steel under laboratory- and actual-scale conditions for flux A. (Online version in color.)
laboratory conditions. Since the kinetic model can calculate the dissolved Mg concentration in steel, the obtained dissolved Mg concentration in the steel is described here. The calculated results under laboratory conditions showed the same tendency as the experimental results, and finally the MgO·Al2O3 inclusions were stable. In contrast, in the actual-scale calculation, the increase in the Mg content in the steel was suppressed before and after Al addition, and the results were outside the stable region of MgO·Al2O3 most of the time. This reason is discussed below. In this calculation model, the rate of change of Mg content in the molten steel is calculated by the following Eqs. (12) and (13).

$$\frac{d[Mg]}{dt} = \left(\frac{A}{V}\right)k_m ([Mg]^* - [Mg]) \quad \cdots \quad (12)$$

$$\log k_m = 1.98 + 0.5 \log \left(\frac{\varepsilon \times 1000}{b_m} \left(\frac{h_t}{d_t}\right)^2\right) - \frac{125000}{2.3RT} \quad \cdots \quad (13)$$

where $A$ is the cross-sectional area of the bath ($m^2$); $V$ is the volume of molten steel ($m^3$); $k_m$ is the mass transfer coefficient of metal ($m/s$); $\varepsilon$ is the stirring energy ($W/t$); $h_t$ is the bath depth ($m$); $d_t$ is the bath diameter ($m$); $R$ is the molar gas constant ($J/K/mol$); $T$ is the temperature of molten steel ($K$); and the superscript “*” indicates the content at the interface between metal and slag.

Although the stirring energy is the same level in both the laboratory experimental conditions and the actual-scale conditions, $k_m$ calculated from the actual-scale conditions is larger because the bath shape is different. On the other hand, the cross-sectional area of bath relative to the volume of molten steel ($A/V$) is larger under laboratory experimental conditions. Based on the above, considering the coefficient ($A/V)\times k_m$, the influence of $A/V$ is dominant that is, $A/V$ under the laboratory experimental conditions is larger, and the increasing rate of Mg content in the molten steel is larger. In other words, it is considered that the increasing rate of Mg content in the molten steel is smaller in the actual-scale conditions than in the laboratory experimental conditions because $A/V$ is smaller in the actual-scale conditions. From this result, the delay of Al addition is considered to be effective for suppressing spinel inclusions under actual-scale conditions.

In addition, the effect of the slag composition and Al addition timing on the inclusion composition was evaluated by this kinetic model calculation. Figures 11 and 12 show the model calculation results when the slag composition and Al addition timing were changed under actual-scale conditions. As in Fig. 10, the calculation results are shown on the phase stability diagram. In the evaluation of the slag composition effect, fluxes A and D used in the laboratory experiment were applied to the calculation. When flux D was used, the increase in the Mg content in the steel was suppressed compared with flux A, and the results were located in the $Al_2O_3$ stable region. The effect of the delayed Al addition was compared with the condition Al addition from the beginning of the reaction. When Al was added from the beginning, the Mg content in the steel increased faster than when Al was added 30 min after flux addition, and finally MgO·Al2O3 was stable. Thus, the results of these kinetic model calculations indicated that Al addition in the middle of the process, in combination with slag composition control, is effective for suppressing formation of spinel-type inclusions at the actual scale.

In order to verify these results, tests were conducted in the bearing steel manufacturing process. Specifically, in the steelmaking process of converter → secondary refining process (LF → RH) → continuous casting, the composition of the LF slag was changed to lower CaO/SiO2 and lower CaO/Al2O3, and the timing of Al addition in the LF was changed from the beginning to the middle of LF treatment. As a result, at the end of LF treatment, the content of T.Mg in the steel was reduced to about one-half of that in the conventional material, and spinel-type inclusions were hardly observed. Therefore, this actual equipment experiment confirmed the validity of slag composition optimization and Al addition in the middle of the process for suppression of spinel-type inclusions.

### 5. Conclusions

In order to suppress the formation of MgO·Al2O3 spinel-type inclusions in high carbon steel, the composition change
of inclusions in the reaction between non-Al deoxidized molten steel and slag and the effect of Al addition at the midpoint on the inclusion composition were evaluated by a laboratory-scale molten steel-slag reaction experiment and calculations based on actual-scale conditions.

(1) As a result of the laboratory-scale molten steel-slag reaction experiment, the average MgO content in the inclusion was less than 10 mass% before Al addition, and spinel-type inclusions were hardly observed. After Al addition, the average MgO content in the inclusions increased rapidly, resulting in the formation of spinel-type inclusions. Both before and after Al addition, the effect of the slag composition on the inclusion composition was large. Compared with the results under the slag conditions of CaO/SiO₂ = 6.7 and CaO/Al₂O₃ = 2.3, when the final slag composition was CaO/SiO₂ = 3.5 and CaO/Al₂O₃ = 0.8, the average MgO content in the inclusions was about one-fifth of that before Al addition and about one-seventh of that after Al addition.

(2) In order to evaluate the effect of Al addition in the middle of the process under actual-scale conditions, a calculation using a kinetic model was carried out. The results indicated that the increase rate of the Mg content in the steel was slower under the actual-scale conditions than under the laboratory-scale conditions, suggesting that the addition of Al in the middle of the process is more effective in suppressing spinel-type inclusions under actual-scale conditions than in the laboratory experiment. Based on these results, the slag composition and Al addition timing in LF treatment were changed in the actual process. As a result, a decrease in the content of T.Mg and suppression of spinel-type inclusions in the steel at the end of the LF treatment were confirmed.

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