1. Introduction

With the requirements for high quality iron and steel products becoming increasingly strict, the requirements for high cleanliness in the molten steel have also become higher. Particularly with regard to high Ni alloys and stainless steels, a molten steel refining process which provides higher cleanliness in comparison with carbon steel has become an important topic in consideration of the applications and quality requirements of those products.

In recent years, the FeO and chrome oxide content of slag has been reduced and high basicity slags have been adopted in order to achieve higher purity, and particularly lower oxygen levels. However, as a result, the formation of MgAl₂O₄ spinel type inclusions in steel, which was rarely seen in the past, has become a problem. Due to the fact that MgAl₂O₄ spinel has a high melting point and displays a different deformation capacity from that of steel, it exists as an inclusion in the form of C type inclusions with a small aspect ratio, and thus reduces the fatigue strength of spring material and bearing materials. Moreover, this type of inclusion has also become a cause of surface defects and other problems in high Ni alloy steels, which are processed by rolling into ultra thin sheets with thickness on the order of \(1.0 \times 10^{-3}\) m, as in shadow masks.

Against this background, research on the formation of MgAl₂O₄ spinel type inclusions has become active in recent years, and thermodynamic studies of the subject have been published. Based on these researches, it has been possible to obtain equilibrium constants for the formation of MgAl₂O₄ spinel, interaction parameters, and other numerical values necessary for investigations based on equilibrium theory. However, study of the influence of slag basicity and similar factors has been limited to qualitative explanations, and study from the viewpoint of kinetics, which is important for practical purposes, has been insufficient.

In the present research, in order to clarify the formation mechanism of MgAl₂O₄ spinel type inclusions in aluminum killed ferritic stainless steel (SUS430), experiments were carried out using a 20 kg high frequency, small scale induction furnace, and the slag, metal, and inclusions were investigated. This research is expected to lead to an inclusion control technique which can be applied to actual VOD operation by controlling the slag composition.

2. Experimental Procedure

Experiments were carried out using the 20 kg high frequency vacuum induction furnace shown in Fig. 1. The induction furnace is housed in a sealed chamber, and the interior of the chamber was maintained at a vacuum of \(1.04 \times 10^5\) Pa (780 Torr) with Ar gas during melting and the experiments. MgO crucible with an inner diameter of \(1.5 \times 10^{-1}\) m and a
A depth of $2.5 \times 10^{-1}$ m was placed in the furnace. The temperature of the molten steel was continuously measured and controlled to maintain at 1 923 K using a thermocouple installed in the crucible, while at the same time, consumable type thermocouples were also immersed at appropriate times and temperature adjustments were made. The temperature in the experiments was $1 923 \pm 10$ K.

The experimental procedure was as follows. First, after reducing the pressure in the chamber, the air was replaced with Ar gas, and the atmospheric pressure was adjusted to $1.04 \times 10^{5}$ Pa. After melting electrolytic iron in the crucible, metallic Cr was added, and 20 kg of molten steel with a composition of 16 mass% Cr was melted while maintaining a temperature at 1 923 K. Next, the components C, Mn, Si, etc. were adjusted, and flux (equivalent to 25 kg/t) was added. After confirming melting of the flux, a prescribed amount of Al was added. Al addition was performed by attaching an Al wire to a round carbon steel rod having a diameter of $1.0 \times 10^{-2}$ m and a length of approximately $1.0 \times 10^{-1}$ m and immersing the rod and wire in the molten steel. By preventing a direct reaction between the Al and slag, this method stabilized the addition yield.

After Al addition, samples of the molten steel were taken successively and rapidly cooled. In order to investigate the changes in the composition of the inclusions contained in the steel, samples were polished to a mirror surface with a diamond abrasive, five to ten representative spots were selected at random using a scanning electron microscope (SEM), and a quantitative analysis of the composition was performed with an energy dispersive type X-ray analyzer (EDX). To determine the concentration of Mg in the steel, a quantitative analysis of the extremely small amounts of this substance was performed by flameless atomic absorption spectrometry.

The compositions of the molten steel and slag used in these experiments are shown in Tables 1 and 2, respectively.

### 3. Experimental Results

As an example of the experimental results obtained with the 20 kg vacuum induction furnace, Fig. 2 shows the changes with time in the composition of the molten iron after Al addition in experiment No. 4. The Al concentration of the steel decreased, beginning immediately after Al addition, while simultaneously, the Si concentration increased. Further, the Mg concentration also increased after Al addition, reaching 0.8 mass ppm after 30 min. Figure 3 shows the changes with time in the composition of the inclusions after Al addition during the same experiment as in Fig. 2. The composition of the inclusions in the steel was simple Al2O3 immediately after Al addition. However, after approximately 2 min, the MgO concentration of the inclusions reached approximately 10 mass%. Thereafter, the MgO concentration increased gradually, apparently corresponding to the increase behavior of the Mg concentration in Fig. 2.

Figure 4 shows an SEM photograph of typical Al2O3–MgO inclusions. The size of the observed inclusions was small, having a diameter of $2.0-4.0 \times 10^{-3}$ m in almost all cases.

In order to confirm that the change in the composition of the inclusions described above was a change in composition from simple Al2O3 inclusions to Al2O3–MgO, an experiment was carried out by first performing top addition of a flux with the same composition as in experiment No. 3 on the molten steel, and then immersing a dense alumina plate.
in the steel for 40 min after Al addition. The results of an observation of the cross section of the alumina plate, which was slow cooled after this experiment, are shown in Fig. 5. From these photographs, it can be understood that the composition had changed from \( \text{Al}_2\text{O}_3 \) to \( \text{Al}_2\text{O}_3-\text{MgO} \) in a range extending from the surface of the alumina plate to a depth of approximately \( 2.0 \times 10^{-3} \text{m} \). It was also found that the concentration of MgO in this degraded layer was virtually uniform in the plate thickness direction, from the molten steel contact surface, at 15–18 mass%.

These observations confirmed that \( \text{Al}_2\text{O}_3 \) is chemically reduced by the Mg contained in the steel and is degraded into \( \text{Al}_2\text{O}_3-\text{MgO} \). It should be noted, however, that the absolute values of the concentration and thickness of the degraded layer were not identical to those at the time of immersion of the alumina plate, because Mg diffusion also occurred during slow cooling after the experiment.

From the above, it is considered that the MgO in inclusions after Al addition is the result of the process in which the MgO contained in the slag is chemically reduced by the Al in the steel, and then the Mg formed by the reduction reacts with the deoxidation product \( \text{Al}_2\text{O}_3 \) to form \( \text{Al}_2\text{O}_3-\text{MgO} \) inclusions.

Figure 6 shows the change with time in the MgO concentration of inclusions after Al addition under various experimental conditions. Although the MgO concentration of the inclusions increases after Al addition, the MgO concentration tends to increase more quickly when the \( \text{CaO}/\text{SiO}_2 \) or \( \text{CaO}/\text{Al}_2\text{O}_3 \) of the slag is high (experiments No. 1, 3). Moreover, because the rate of the increase in the MgO concentration becomes slow when the MgO concentration of the inclusions reaches 25–27 mass%, it is considered that the composition of the inclusions has changed from \( \text{Al}_2\text{O}_3 \) to MgAl\(_2\)O\(_4\) positive spinel (\( \text{Al}_2\text{O}_3 : \text{MgO} = 72 \text{mass} \% : 28 \text{mass} \% \)).

Furthermore, although an MgO crucible was used in this research, the composition of the inclusions was \( \text{Al}_2\text{O}_3 \) throughout experiments under slag-free conditions. From this fact, it is considered that the MgO concentration of the inclusions was not affected by the MgO crucible.

4. Discussion

From the results described in the previous chapter, it was understood that the concentration of MgO in inclusions increases with the passage of time after Al addition, and the rate of increase in the concentration of MgO in inclusions is influenced by the slag composition. The formation of MgO concentration of inclusions after Al addition under various experimental conditions. Although the MgO concentration of the inclusions increases after Al addition, the MgO concentration tends to increase more quickly when the \( \text{CaO}/\text{SiO}_2 \) or \( \text{CaO}/\text{Al}_2\text{O}_3 \) of the slag is high (experiments No. 1, 3). Moreover, because the rate of the increase in the MgO concentration becomes slow when the MgO concentration of the inclusions reaches 25–27 mass%, it is considered that the composition of the inclusions has changed from \( \text{Al}_2\text{O}_3 \) to MgAl\(_2\)O\(_4\) positive spinel (\( \text{Al}_2\text{O}_3 : \text{MgO} = 72 \text{mass} \% : 28 \text{mass} \% \)).

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Furthermore, although an MgO crucible was used in this research, the composition of the inclusions was \( \text{Al}_2\text{O}_3 \) throughout experiments under slag-free conditions. From this fact, it is considered that the MgO concentration of the inclusions was not affected by the MgO crucible.
in inclusions consists of two element processes, one being a reaction between the metal and the slag, in which the MgO in the slag is chemically reduced by the Al in the molten steel, and another being a reaction between the metal and inclusions, in which the deoxidation product Al2O3 reacts with the Mg in the steel that was formed by chemical reduction of the slag. Figure 7 shows these two elemental processes in schematic form.

In order to estimate the rate-determining step in these respective element processes, the slag–metal reaction was investigated from the viewpoint of kinetics in the following Sec. 4.1, and the metal–inclusion reaction was similarly investigated in Sec. 4.2.

4.1. Kinetics of Reduction of MgO in Slag
4.1.1. Slag–Metal Reaction Model

In order to analyze the reduction reaction of the MgO in slag in the 20 kg small scale induction furnace experiments from the viewpoint of kinetics, the authors adopted a competing reaction model based on two film theory, which is frequently applied to dephosphorization/desulfurization reactions in molten iron and to reoxidation reactions in molten steel by slag. In the following, this will be referred to in abbreviated form as the reaction model.

It is assumed that the concentrations of Al2O3, SiO2, and MgO in the slag side and of Al, Si, Mg, and O in the metal side show respective concentration gradients in the double boundary film layer at the slag–metal interface, and have reached a thermodynamic equilibrium at the interface.

Assuming that the reactions in Eqs. (1)–(3) have reached equilibrium at the slag–metal interface, the equilibrium constants for these reactions can be expressed by Eqs. (4)–(6). Further, AlO1.5 is adopted for the sake of computational simplicity, and because the concentrations of iron and chromium oxides in the slag were extremely low in the experiments with the small scale induction furnace, these reactions are not considered.

\[
\begin{align*}
[Al] + 1.5[O] &= (AlO_{1.5}) \quad \cdots \quad (1) \\
[Si] + 2[O] &= (SiO_2) \quad \cdots \quad (2) \\
[Mg] + [O] &= (MgO) \quad \cdots \quad (3)
\end{align*}
\]

\[
\begin{align*}
K_{Al} &= a^{*}_{AlO_{1.5}} \cdot (a^{*+}_{Al} \cdot a^{*+}_{O}) \quad \cdots \quad (4) \\
K_{Si} &= a^{*}_{SiO_2} \cdot (a^{*+}_{Si} \cdot a^{*+}_{O}) \quad \cdots \quad (5) \\
K_{Mg} &= a^{*}_{MgO} \cdot (a^{*+}_{Mg} \cdot a^{*+}_{O}) \quad \cdots \quad (6)
\end{align*}
\]

If it is assumed that the rate of the chemical reactions involving the respective components at the slag–metal inter-

\[
\begin{align*}
\frac{d[Al]}{dt} &= -A \cdot k_{Al} \cdot \frac{[Al]}{W_m} \cdot \left(\frac{AlO_{1.5}}{B_{Al} \cdot a^{*+1.5}_{O}}\right) \quad \cdots \quad (7) \\
\frac{d[Si]}{dt} &= -A \cdot k_{Si} \cdot \frac{[Si]}{W_m} \cdot \left(\frac{SiO_2}{B_{Si} \cdot a^{*2}_{O}}\right) \quad \cdots \quad (8) \\
\frac{d[Mg]}{dt} &= -A \cdot k_{Mg} \cdot \frac{[Mg]}{W_m} \cdot \left(\frac{MgO}{B_{Mg} \cdot a^{*2}_{O}}\right) \quad \cdots \quad (9) \\
\frac{d[O]}{dt} &= A \cdot k_{O} \cdot \frac{[O]}{W_m} \cdot \left(\frac{a^{*}_{O}}{f^{*}_{O}}\right) \quad \cdots \quad (10)
\end{align*}
\]

\[
B_{i} = \frac{k_{i} \cdot f_{i} \cdot C}{M_{iO} \cdot \gamma_{i}} \quad \cdots \quad (11)
\]

\[
C = \sum \left(\frac{\gamma_{si}O_{si}}{M_{O}}\right) \quad \cdots \quad (12)
\]

\[
\frac{1}{k_{i}} = \frac{1}{\rho_{m} \cdot k_{m}} + \frac{1}{k_{is}} \quad \cdots \quad (13)
\]

Oxygen activity, \(a^{*}_{O}\), at the slag–metal interface can be obtained from the above equations and the mass balance equation for oxygen at the interface, Eq. (14). Here, \(M\) is the molecular weight, and \(\gamma\) is the activity coefficient.

\[
\begin{align*}
\frac{1.5}{M_{Al}} \frac{d[Al]}{dt} + 2 \frac{2}{M_{Si}} \frac{d[Si]}{dt} &+ \frac{1}{M_{Mg}} \frac{d[Mg]}{dt} + \frac{1}{M_{O}} \frac{d[O]}{dt} = 0 \quad \cdots \quad (14)
\end{align*}
\]

If this \(a^{*}_{O}\) and the appropriate mass transfer coefficients for molten steel and slag are given, it is possible to obtain the reaction velocities of the respective components between the slag and metal. It was assumed that the mass transfer coefficient, \(k_{is}\), on the metal side has an identical value for all the components, including Mg.

On the other hand, it was assumed hypothetically that the mass transfer coefficients for SiO2 on the slag side, \(k_{is}\), have different values from the other components, as has been reported in connection with previous research.

Under these assumptions, the mass transfer coefficient for the metal side, \(k_{im}\), and the mass transfer coefficient for the slag side, \(k_{is}\), were obtained so as to agree with the experimental results. As a result, it was possible to obtain the calculated result which showed the closest agreement with the experimental results when the metal side mass transfer coefficient, \(k_{im}\), was \(2.0 \times 10^{-4} \text{ m/s}\), the slag side mass transfer coefficient of the components other than SiO2, \(k_{is}\), was \(1.0 \times 10^{-5} \text{ m/s}\), and the slag side mass transfer coefficient of SiO2 was \(2.0 \times 10^{-6} \text{ m/s}\).
Figure 8 shows the observed results of the change with time in the concentration of Al and Si in the molten steel in experiment No. 4, in comparison with the results calculated based on the model described above. Figure 9 shows the observed results of the concentration of Mg in the molten steel, in comparison with the results obtained by calculation. From these figures, the calculated results of the change with time in the concentrations of Al, Si, and Mg in the molten steel showed good agreement with the experimental results.

Based on the results described above, the mass transfer resistance of the respective components on the metal side and slag side in experiment No. 4 was obtained using Eq. (13), as shown in Table 3. From this table, it can be inferred that the reactions in Eqs. (1) and (3), which are due to slag–metal reactions, are the rate-determining steps of mass transfer on the metal side, and the reaction in Eq. (2) is rate-determining for mass transfer on the slag side.

4.1.2. Influence of Slag Composition on Rate of Increase in Concentration of Mg in Molten Steel Due to Reduction Reaction of MgO in Slag

If it is assumed, based on the previous section, that the reaction in Eq. (3) is rate-determining for mass transfer on the metal side, and the reaction velocity is expressed considering only the mass transfer on the metal side, then Eq. (15) can be deduced using the concentration gradient in the boundary film on the metal side.

\[
\frac{d[Mg]}{dt} = \left( \frac{A \cdot k_{m}}{V} \right) \cdot ([Mg]^* - [Mg]) \quad (15)
\]

From this equation, it can be understood that the rate of increase in the Mg concentration of the molten steel depends on the Mg concentration, \([Mg]^*\), at the slag–metal interface. The slag composition dependency of \([Mg]^*\) at the slag–metal interface will be considered qualitatively in the following.

\([Mg]^*\) can be determined by the activity of MgO, \(a_{MgO}^*\), and the activity of oxygen, \(a_{O}^*\), at the slag–metal interface using Eq. (6).

Figure 10 shows the calculated relationship between the slag basicity, CaO/SiO\(_2\), and CaO/Al\(_2\)O\(_3\), and the activity of MgO, \(a_{MgO}^*\), the latter being obtained using the thermodynamic data base software Thermo-calc. The value of \(a_{MgO}^*\) increases as the basicity, CaO/SiO\(_2\) and CaO/Al\(_2\)O\(_3\), of the slag increases.

Figure 11 shows the relationship between the slag basicity, CaO/SiO\(_2\), and the activity of dissolved oxygen in the molten steel calculated at the slag/metal interface, comparing with measured dissolved oxygen 10 min after Al addition.
creases.

From the points mentioned above, it can be understood qualitatively that \([\text{Mg}]^*\) at the slag–metal interface increases as the slag has higher basicity, as indicated by \(\text{CaO}/\text{SiO}_2\) and \(\text{CaO}/\text{Al}_2\text{O}_3\), and consequently, the rate of increase in the Mg concentration of the molten steel due to the reduction reaction with the MgO in the slag also increases.

4.2. Kinetics of Metal–Inclusion Reaction

As discussed above, the change in the composition of inclusions produced by Al deoxidation is the result of a process in which the deoxidation product Al2O3 is degraded to an Al2O3–MgO composition by the reaction with the [Mg] in molten steel, the latter being formed when the MgO in the slag was chemically reduced by the Al.

Analyses were performed for the case in which the diffusion of Mg in the inclusion layer is rate-determining, assuming hypothetically that the rate of the chemical reaction at the metal–inclusion interface is sufficiently large, and for the case in which the diffusion of Mg in molten steel is rate-determining.

It is assumed that the Mg in molten steel reacts with Al2O3 inclusions from outside the inclusions, forming a reaction product layer which is composed of Al2O3–MgO. Moreover, in order to simplify the model, it is also assumed that the shape of inclusion particles is spherical, with a radius of \(R_0\), and the outer diameter of the particles does not change over time. The phase diagram for MgAl2O4 spinel shows that the concentration of MgO is 10–28 % at 1 923 K; it was therefore assumed that the MgO concentration is 10 % when the inclusions initially begin to form spinel, and the MgO concentration finally changes to 28 % spinel.

4.2.1. Case When Mg Diffusion in Inclusion Layer Is Rate-determining Step

Figure 12 shows a schematic diagram of the distribution of the Mg concentration in an inclusion in the case when the diffusion of Mg in the inclusion layer is rate-determining. In actuality, because expansion of the spinel layer progresses by diffusion of Mg and Al into a shell-like spinel layer, it is considered that the concentration profile takes a form similar to that shown in Fig. 12. Here, however, for the sake of simplicity, it was thought that Mg is transferred by diffusion in an inclusion with an initial (Mg) concentration of 0 mass%. Therefore, the diffusion coefficient of Mg in MgAl2O4 spinel was used as the diffusion coefficient in this case. The equation for diffusion in an inclusion can be expressed by Eq. (16).

\[
\frac{d(\text{MgO})}{dt} = \frac{D_s}{r^3} \frac{d}{dr} \left( r^2 \frac{d(\text{MgO})}{dr} \right) \quad \text{...(16)}
\]

It was assumed that when \(t = 0\), \(r = R_0\), and (MgO) = 28 mass%, and when \(r\) does not equal \(R_0\), (MgO) = 0 mass%. Further, it was assumed that the MgO concentration at the boundary phase between the spinel phase and Al2O3 is 10 mass%. Figure 13 shows the results when the change in the MgO concentration of the inclusion as a whole is obtained for each inclusion particle size by calculating the above equation by the calculus of finite differences. Here, \(D_s = 3.2 \times 10^{-13} (\text{m}^2/\text{sec})^9\) was used as the inter-diffusion coefficient in MgAl2O4 spinel.

From the same figure, it can also be understood that diffusion within inclusions progresses extremely rapidly, and at an inclusion particle size on the order of 3 \(\mu\)m, as observed in these experiments, the MgO concentration reaches saturation in approximately 2 sec.

4.2.2. Case When Mg in Molten Steel Is Rate-Determining Step

The case when the MgO concentration distribution in the inclusion changes uniformly, under the assumption that the diffusion of Mg in inclusions is sufficiently rapid, can be represented as shown in Fig. 14. From the balance of Mg on the metal side and in the inclusions:
[Mg] is Mg concentration at metal at the metal–inclusion interface. And (Mg)' is Mg concentration of inclusion at the metal–inclusion interface. Here, based on the fact that the inclusion particle size is extremely small, at 2.0–4.0×10^{-6} m, only the diffusion within the boundary layer on the metal side was considered in mass transfer.

The distribution ratio, L, is the equilibrium distribution ratio of Mg at the metal–inclusion interface. Using the above equation, the change with time in the concentration of MgO in molten steel due to the slag–metal reaction achieves equilibrium in approximately 30 min. Based on this fact, it can be inferred that the slag–metal reaction is the slowest among the various element processes. Thus, in the system as a whole, this reaction is the rate-determining step for inclusion formation, including that of MgO.

Therefore, Eq. (17) was calculated considering the time related change in [Mg] in molten steel. If [Mg] is expressed as shown in Eq. (15), and assuming that the Mg concentration at the slag–metal interface, [Mg]*, is constant, the time related change in [Mg] in molten steel can be expressed by the following equation.

\[
[Mg] = [Mg]* \left(1 - \exp \left(-\frac{A \cdot K_m}{V} \cdot t\right)\right) \quad \cdots \cdots (20)
\]

Here, assuming (Mg)'=0 when t=0, the MgO concentration in inclusions can be expressed by the equation shown below.

\[
[Mg] = [Mg]* - \frac{[Mg]* \cdot L}{3D_m \cdot \rho_m \cdot \rho_i} \left(\frac{A \cdot K_m}{V} \cdot \exp \left(-\frac{3D_m \cdot \rho_m}{R_0^2 \cdot L \cdot \rho_i} \cdot t\right)\right) \quad \cdots \cdots (21)
\]

Figure 16 shows the time related change in the MgO concentration in inclusions obtained using Eq. (21), together with the observed values. The calculated values can pro-
vide a rough explanation of the observed values. The calculated values and observed values do not show good agreement in the initial stage of the reaction. This may be attributed to the fact that the equilibrium distribution value, \( L \), of Mg at the metal–inclusion interface, and Mg concentration, \([\text{Mg}]^*\), at the metal–slag interface are assumed to be constant; whereas, in actualy, the value of \( L \) in the initial stage of the reaction is larger than the value used in the calculation.

5. Conclusion

In order to clarify the mechanism by which \( \text{Al}_2\text{O}_3–\text{MgO} \) inclusions form in chrome-bearing molten steel, experiments were performed with a 20 kg high frequency induction furnace, and the slag–metal–inclusion reaction was investigated from the viewpoint of kinetics. The results were as follows.

(1) An investigation of the influence of the slag composition on the formation of \( \text{MgO}–\text{Al}_2\text{O}_3 \) inclusions showed that the Mg concentration of the molten steel increases with time after the addition of Al, and accompanying this increase, the composition of inclusions changes from simple \( \text{Al}_2\text{O}_3 \) to \( \text{MgAl}_2\text{O}_4 \) spinel having an MgO concentration of 23–27 mass%. The rate of increase in the MgO concentration of the inclusions also increased as the basicity, \( \text{CaO}/\text{SiO}_2 \) and \( \text{CaO}/\text{Al}_2\text{O}_3 \), of the top slag increased.

(2) A comparison of the calculated results of a slag–metal reaction model based on two film theory and the experimental results showed good agreement between the two. In the composition range used in these experiments, it was inferred that the increase in the concentration of \( [\text{Mg}] \) in the molten steel is the rate-determining step for mass transfer on the metal side. The results also showed that the influence of the slag composition on the rate of increase in the Mg concentration of inclusions can be explained by changes in the \( [\text{Mg}] \) concentration at the slag–metal interface due to the slag composition dependency of MgO activity, \( a_{\text{MgO}} \), and oxygen activity, \( a_{\text{O}} \), at the interface.

(3) As a result of a kinetic analysis of the respective conditions under which Mg diffusion in inclusions is the rate-determining step for the metal–inclusion reaction, and under which Mg diffusion in the molten steel is rate-determining, it was inferred that the latter is the rate-determining step. Furthermore, with the inclusion particle size observed in these experiments, the metal–inclusion reaction is sufficiently faster than the slag–metal reaction. Consequently, it can be concluded that, in the system as a whole, the slag–metal reaction is the rate-determining step for the rate of inclusion formation, including that of MgO.

Nomenclature

- \( A \): Area of reaction interface (m²)
- \( a_i \): Activity of component \( i \) (molten steel component)
- \( f_i \): Activity coefficient of component \( i \)
- \( K_i \): Equilibrium constant of \( i + n\text{O} = i\text{O}_n \)
- \( k_i \): Total mass transfer coefficient of component \( i \) (g/m²·s)
- \( k_m \): Mass transfer coefficient of metal side (g/m²·s)
- \( k_s \): Mass transfer coefficient of slag side (g/m²·s)
- \( L \): Distribution ratio of Mg between metal and inclusions (—)
- \( M_i \): Molecular weight of component \( i \)
- \( N_i \): Mole fraction of component \( i \)
- \( R \): Radius of inclusion particle (m)
- \( V \): Volume of molten steel (m³)
- \( W_m \): Mass of molten steel (kg)
- \( \gamma_i \): Activity coefficient of component \( i \)
- \( \rho_m \): Density of metal (assumed to be 7 000 kg/m³)
- \( \rho_s \): Density of slag (assumed to be 2 700 kg/m³)

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