Dissolution Behavior of Mg from MgO into Molten Steel Deoxidized by Al

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The formation of MgO-Al2O3 spinel-type inclusions has often been reported even when Mg is not added during treatment. Many researchers have investigated the dissolution behavior of Mg from slag; however, studies on the reaction between molten steel and MgO-type refractory are limited. In this paper, the inclusion composition of Al-deoxidized steel melted in a MgO crucible, and mass transfer rates of Mg from a MgO rod and MgO in slag to Al-deoxidized molten steel were investigated. These studies clarified that Mg dissolved in the molten steel and the spinel formed not only with the reaction of molten steel and slag but also with the reaction of molten steel and MgO crucible. The dissolution rate of Mg from MgO rod increased as the rotation rate and Al content in steel increased. The MgO-Al2O3 spinel layer formed at the interface between the metal and MgO rod. The Mg content was higher for the reaction between molten steel and MgO in slag compared to the reaction between molten steel and MgO rods, as it equilibrated with MgO activity in slag.

KEY WORDS: inclusion; spinel; MgO; refractory; dissolution; slag; composition change.

1. Introduction

As the demand for high-quality steel continues to increase, the ladle refining process has become increasingly important for obtaining molten steel with a suitable composition and cleanliness. The precise control of the inclusion composition is very important. However, the reactions in the ladle treatment of steel are very complex as they simultaneously occur among the molten steel, slag, and refractory.

In addition, the formation of MgO-Al2O3 spinel-type inclusions has often been reported even when Mg is not added during the treatment.1) The spinel-type inclusion often causes surface flaws and cracking because of its high melting temperature and low deformability. It also raises a serious problem for operations by causing nozzle clogging. From a thermodynamic consideration, it is presumed that Mg is formed in molten steel through the reduction of MgO in the slag or refractory by Al, which is added to molten steel as a deoxidizer.

Many researchers have investigated the dissolution behavior of Mg in the reaction between molten steel and slag; however, studies on the reaction between molten steel and MgO-type refractory are limited. Wanibe et al.2) studied the reaction between molten iron and MgO crucible and deduced that the dissolution of Mg from the refractory occurs through a change in O content. Ito et al.3) and Matsuno et al.4) measured the inclusion composition of Al-deoxidized steel melted in a MgO-type crucible. According to their experimental results, Mg dissolved in the molten steel, and a MgO-Al2O3 spinel-type inclusion formed. Jansson et al.5) investigated the effect of relative velocity, temperature, and steel composition on the dissolution rate of MgO–C refractory in Al-deoxidized molten steel by the rotating cylinder method. However, the change in Mg content over time was unclear in their experiments. It is important to know the dissolution behavior of Mg from refractory to control the inclusion composition. Therefore, in this study, the inclusion composition of MgO–Al2O3 refractory in molten steel was measured, and an empirical equation was established. Finally, the behavior of Mg in the reaction between molten steel and MgO rod was compared to the reaction between molten steel and MgO in slag.

2. Experimental Method

2.1. Inclusion Composition of Al-deoxidized Steel Melted in a MgO Crucible

The experimental setup is shown in Fig. 1. Two hundred grams of metal and 10 g of slag were placed in a MgO crucible having an inner diameter of 32 mm and a height of 100 mm. The composition of metal and slag are listed in
To adjust the metal composition, electrolytic iron, carbon, FeS, Fe–20mass%Mn alloy, and Fe–2mass%Al alloy were loaded in a MgO crucible. Fe–20mass%Mn alloy and Fe–2mass%Al alloy were previously made using an arc furnace. Slag was prepared by melting CaO, Al2O3, MgO, SiO2, Fe2O3, and electrolytic iron in an Al2O3 crucible at 1 723 K. CaO was made by heating CaCO3 at 1 273 K for 3 h in an Al2O3 crucible. The MgO crucible with alloy and slag was placed in a high-frequency induction furnace. As slag is not heated by electromagnetic induction, a carbon crucible was set to heat the slag around the upper part of the MgO crucible. An Al2O3 tube with an inner diameter of 16 mm was inserted into the furnace for sampling, temperature measurement, and alloy addition. The top of the tube was sealed by silicon rubber. Before heating, the atmosphere in the furnace was replaced by purified Ar gas. The temperature of the molten steel was controlled at 1 873 K using a pyrometer corrected by a thermocouple. After the temperature was reached, the silicon rubber of the tube was sampled. The samples were quenched in water. The composition of metal and slag were analyzed by ICP-AES. The total O content in the metal was analyzed by a fusion-infrared absorption method. The morphology and composition of inclusions were observed by FE-SEM with EDX. An experiment without slag was also performed by the same method for comparison.

### 2.2. Reaction with MgO Rod and Molten Steel Deoxidized by Al

The experimental set up is shown in Fig. 2. Two hundred grams of electrolytic iron and pure Al were charged into an Al2O3 crucible with an inner diameter of 33 mm and a height of 100 mm. In this experiment, the Al2O3 crucible was used to keep the Al content high, and the target value of Al content was between 0.1 and 0.3 mass%. The Al2O3 crucible with alloy was set in a high-frequency induction furnace. Around the Al2O3 crucible, a carbon crucible was set to suppress the induction stirring of the metal phase. The atmosphere in the furnace was replaced by purified Ar gas before heating. Compared to experiment 2.1, the sealing condition of the furnace was improved in this experiment to avoid the oxidation of Al by air leakage. In addition, to keep the inert atmosphere in the furnace, sampling was not conducted during the experiment. Therefore, to obtain the composition change behavior over time, experiments were carried out under the same conditions with changing experimental times. The temperature of molten steel was controlled at 1 873 K using a pyrometer corrected by a thermocouple. After reaching the temperature, a MgO rod 6 mm in diameter was dipped into the molten steel and rotated at
a rate of 100–400 rpm. The time to dip the MgO rod was set as the start time of the experiment. Before immersion, the MgO rod was placed just above the molten metal for preheating. The depth of the rod dipped in metal was 30 mm. The experimental time was changed from 2.5 to 60 min. After that, the crucible with melt was quenched in water. The parameters varied in each experiment are listed in Table 3. The chemical composition of Al and Mg in the metal was analyzed by ICP-AES. The total O content in the metal was analyzed by fusion and the infrared absorption method. The interface between the metal and MgO rod after experiments was observed by EPMA.

2.3. Reaction with MgO in Slag with Molten Steel Deoxidized by Al

The experimental set up is shown in Fig. 3. One hundred grams of electrolytic iron and 15 g of slag pellet were charged in a MgO crucible with an inner diameter of 32 mm and a height of 100 mm. The composition of slag is listed in Table 4 and plotted on the phase diagram in Fig. 4. As the slag was saturated with MgO, the activity of MgO was unity. To make a slag pellet, CaO, Al₂O₃, and MgO powder were mixed and pressed to form a disc 13 mm in diameter, and the disc was sintered at 1 273 K for 12 h. The MgO cru-

<table>
<thead>
<tr>
<th>Table 3. Experimental parameters to investigate the reaction between the MgO rod and molten steel.</th>
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<tbody>
<tr>
<td>Target value of Al</td>
</tr>
<tr>
<td>(mass%)</td>
</tr>
<tr>
<td>0.1, 0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Initial composition of slag to investigate the reaction between MgO in slag and molten steel (mass%).</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
</tr>
<tr>
<td>45</td>
</tr>
</tbody>
</table>

Fig. 3. Schematic diagram of the experimental set up to investigate the reaction between MgO in slag and molten steel.

Fig. 4. Slag composition to investigate the inclusion composition of steel melted in a MgO crucible on the phase diagram of a CaO–MgO–Al₂O₃ system at 1 873 K.

Fig. 5. Change in the Al, Mg, and O content during the experiments to investigate the inclusion composition of steel melted in a MgO crucible.
cible with electrolytic iron and slag was set in a high-frequency induction furnace. The atmosphere in the furnace was replaced by purified Ar gas before heating. After the temperature reached 1873 K, pure Al or Fe–2mass%Al alloy was added as a deoxidizer through an Al2O3 tube 16 mm in diameter. Fe–Al alloy or pure Al with iron particles was held at the upper part of the tube by a magnet prior to the experiment to maintain the inert atmosphere in the furnace. The target value of Al content was 0.3 mass%. The time when the deoxidizer was added was set as the start of the experiment. After holding for the predetermined time (2.5–60 min), the crucible with melt was quenched in water. The analysis methods for the chemical composition of the metal were the same as in the previous section.

3. Results and Discussion

3.1. Inclusion Composition of Al-deoxidized Steel Melted in a MgO Crucible

3.1.1. Experimental Results

Figure 5 shows the change in Al, Mg, and O content over time for the experiments with and without slag. Upon the addition of deoxidizer, Al content increased; however, it gradually decreased over the experimental time in each case. This decrease is caused by the reaction with O in the atmosphere, slag, and crucible. In both experiments, the dissolution of Mg in the molten steel was observed. The Mg content in the experiment with slag was higher than that without slag. However, Mg and O content widely varied over time. These variations were caused by the unstable O content in the atmosphere as the silicon rubber of the tube opened frequently for sampling. Figure 6 shows the typical inclusions in the metal samples at 1 and 10 min observed by FE-SEM with EDS. In both experiments, the inclusions were alumina or alumina with a small amount of MgO at 1 min. In addition to these inclusions, at 10 min after deoxidation, spinel-type inclusions were observed. The change in the average composition of 10 inclusions in each sample over time is shown in Fig. 7. Initially, most of the inclusions were alumina, and the MgO content gradually increased until 15 min. After that, the MgO and Al2O3 content decreased, and SiO2 and MnO content increased. The change in the later stage of the experiment was caused by the decrease in Al content in the molten steel. However, the difference in the inclusion composition upon slag addition was not clear. This result indicates that the change of the inclusion composition from alumina to spinel occurs not only with the reaction of molten steel and slag but also with the reaction of molten steel and MgO crucible.

3.1.2. Discussion about the Composition of Inclusions

To investigate the stable composition of inclusions, a phase stability diagram for MgO, MgO·Al2O3, and Al2O3 was calculated. The method for creating it is described in Ref. 6). Figure 8 shows the phase stability diagram with the experimental results. The results in the experiments with/without slag were located at a spinel stable region from 1 min to 20 min. Thus, the composition of molten steel was moved to the spinel stable region by Al deoxidation. This result shows that the Mg content of molten steel increases with the reaction of molten steel and slag and also with the reaction of molten steel and MgO crucible. However, in each case, not only spinel but also alumina was observed, even though the composition of Al and Mg was located in

<table>
<thead>
<tr>
<th>Slag</th>
<th>1 min.</th>
<th>10 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>With</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>2.5</td>
<td>19.2</td>
</tr>
<tr>
<td>Al2O3</td>
<td>95.1</td>
<td>76.1</td>
</tr>
<tr>
<td>Others</td>
<td>2.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Without</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>6.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Al2O3</td>
<td>74.7</td>
<td>75.8</td>
</tr>
<tr>
<td>Others</td>
<td>18.5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Fig. 6. Morphology and composition of typical inclusions observed by FE-SEM with EDS.
the spinel stable region. This discrepancy could be caused by the slow reaction rate for the change from alumina to spinel, as this reaction is controlled by mass transfer in solid alumina.

3.2. Reaction with MgO Rod and Molten Steel Deoxidized by Al

3.2.1. Experimental Results

The changes in the content of Al, Mg, and O with time are shown in Figs. 9 and 10. Al content was almost constant and high during the experiment. Mg content increased in the early stage and became almost constant after ~15 min. In the samples of 0.1 and 0.3 mass% Al, the Mg contents were ~0.6 and 1.3 mass ppm, respectively. The O content in each sample was about 5 ppm.

Figure 11 shows the mapping images of EPMA at the interface between metal and a MgO rod rotating at 100 rpm.
in Fe–0.3mass%Al molten steel after 15 min. The reaction layer containing Al2O3 was confirmed at the interface, and from the quantitative analysis results, the composition of the layer was MgO·Al2O3 spinel, as shown in Fig. 12. The formation of a spinel layer at the interface between the metal and MgO rod was also observed in other samples, and the thickness of the layer gradually increased with time. On the other hand, although a similar layer was observed at the interface between metal and crucible, its thickness was much smaller than that between the metal and MgO rod.

3.2.2. Discussion about the Mg Content in Steel and Dissolution Rate of MgO Rod

As shown in Figs. 9 and 10, MgO rod was dissolved in molten steel deoxidized by Al, and the Mg content increased. The reaction causing the increase in Mg in the molten steel is expressed as follows.

\[
3\text{MgO} + 2\text{Al} = 3\text{Mg} + \text{Al}_2\text{O}_3 \quad \text{(1)}
\]

This reaction indicates that the MgO rod is reduced by Al in the molten steel and forms Mg. In addition to the dissolution of Mg, the spinel formation at the interface between the metal and MgO rod was also observed. The reaction of spinel formation is thought to be the following.

\[
\begin{align*}
\text{Mg} + \text{O} + \text{Al}_2\text{O}_3 & = \text{MgO} \cdot \text{Al}_2\text{O}_3 \quad \text{(2)} \\
\text{MgO} + 2\text{Al} + 3\text{O} & = \text{MgO} \cdot \text{Al}_2\text{O}_3 \quad \text{(3)} \\
\text{Mg} + 2\text{Al} + 4\text{O} & = \text{MgO} \cdot \text{Al}_2\text{O}_3 \quad \text{(4)}
\end{align*}
\]

Equation (2) represents the reaction between Al2O3 and
Mg formed by the reaction shown in Eq. (1). Equation (3) represents the reaction between the MgO rod and Al, and Eq. (4) represents the reaction between Mg and Al in molten steel.

The free-energy change of formation (ΔG) of the reactions shown in Eqs. (2)–(4) is expressed by Eqs. (5)–(7).

\[
\Delta G_{(2)}^{(0)} = -110.677.14 - 93.52T \quad [\text{J/mole}] \quad (8)
\]

\[
\Delta G_{(3)}^{(0)} = -888.097.86 - 210.93T \quad [\text{J/mole}] \quad (9)
\]

\[
\Delta G_{(4)}^{(0)} = -978.094.84 - 128.98T \quad [\text{J/mole}] \quad (10)
\]

The free-energy change of formation for each reaction during the experiment was calculated. In this calculation, the activities of Mg and Al were calculated using the concentration of each element and the activity coefficient. The activity of O was calculated using the equilibrium relationship with spinel in this experimental system. These calculation results were in good agreement with the experimental results after 15 min. Therefore, it can be considered that the Mg content was determined by the equilibrium relationship with spinel in this experimental system.

The free-energy change of formation of Mg, Al, MgO, and Al2O3 are assumed to be unity. The free-energy change of formation (ΔG) of the reactions shown in Eqs. (2)–(4) is expressed by Eqs. (5)–(7).

\[
\Delta G_{(2)}^{(0)} = \Delta G_{(3)}^{(0)} + R \ln \left( \frac{a_{\text{Mg}} \cdot a_{\text{Al}}^{2} \cdot a_{\text{O}}^{2}}{a_{\text{MgO}} \cdot a_{\text{AlO}}^{2}} \right) \quad (5)
\]

\[
\Delta G_{(3)}^{(0)} = \Delta G_{(4)}^{(0)} + R \ln \left( \frac{a_{\text{Mg}} \cdot a_{\text{Al}}^{2} \cdot a_{\text{O}}^{2}}{a_{\text{MgO}} \cdot a_{\text{AlO}}^{2}} \right) \quad (6)
\]

\[
\Delta G_{(4)}^{(0)} = \Delta G_{(4)}^{(0)} + R \ln \left( \frac{a_{\text{Mg}} \cdot a_{\text{Al}}^{2} \cdot a_{\text{O}}^{2}}{a_{\text{MgO}} \cdot a_{\text{AlO}}^{2}} \right) \quad (7)
\]

where ΔG(n) is the free-energy change of formation (J/mol), ΔG(0) is the standard free-energy change of formation (J/mol), R is the gas constant (J/(mol·K)), T is the temperature of the molten steel (K), and a is activity. Subscript of (n) indicates the reaction shown in Eq. (n).

The standard free-energy changes in Eqs. (5)–(7) are expressed as follows using the thermodynamic data: 7

\[
\Delta G_{(2)}^{(0)} = -110.677.14 - 93.52T \quad [\text{J/mole}] \quad (8)
\]

\[
\Delta G_{(3)}^{(0)} = -888.097.86 - 210.93T \quad [\text{J/mole}] \quad (9)
\]

\[
\Delta G_{(4)}^{(0)} = -978.094.84 - 128.98T \quad [\text{J/mole}] \quad (10)
\]

The dissolution rate of Mg increased with the increase in the rotation rate of the MgO rod. It is notable that the mass transfer in molten metal is a rate-controlling step and the concentration difference of Mg in steel with the equilibrium value determined by Eq. (4) is the driving force for the dissolution of MgO. In this case, the molar flux of Mg (J/Mg) is expressed by Eq. (11).

\[
J_{\text{Mg}} = k \left( C_{\text{Mg}}^{\text{eq}} - C_{\text{Mg}} \right) \quad (11)
\]

where k is the mass transfer coefficient of Mg (m/s), and C_{Mg}^{eq} and C_{Mg} are the molar concentrations of Mg at the interface and bulk, respectively (mol/m^3). Eq. (11) is rewritten by Eq. (12).

\[
\frac{d[\text{Mg}]}{dt} = \frac{A \rho_m k}{W} \left( [\%\text{Mg}]^{\text{eq}} - [\%\text{Mg}] \right) \quad (12)
\]

where [\%Mg]^{eq} and [\%Mg] are the mass concentrations of Mg at the interface and bulk, respectively (mass%), t is time (s), A is the interfacial area between molten steel and the MgO rod (m^2), \rho_m is the density of molten steel (kg/m^3), and W is the weight of molten steel (kg). Then, Eq. (13) is obtained by the integration of Eq. (12).

\[
\frac{W}{A \rho_m} \ln \left( \frac{[\text{Mg}]^{\text{eq}} - [\text{Mg}]}{[\text{Mg}]^{\text{eq}} - [\text{Mg}]} \right) = k t \quad (13)
\]

where [\%Mg]^{eq} is the mass concentration of Mg in bulk at 0 min. [\%Mg] was 0.00013 mass% in Fe–0.3mass%Al because [\%Mg] was determined by the equilibrium with the spinel as mentioned above. Based on the relationship between the left side term of Eq. (13) with time, the mass transfer coefficient can be estimated. Figure 14 shows the
example to calculate the mass transfer coefficient in Fe–
0.3 mass% Al molten steel at a rotating rate of 200 rpm. In
the same way, the mass transfer coefficients of the other
experiments were evaluated as listed in Table 5. The mass
transfer coefficient increased with an increase in the rotation
rate of the MgO rod. The mass transfer coefficient that con-
trols the dissolution rate of solid into liquid under forced
convection has already been studied in many systems, and
some non-dimensional equations have been proposed. For
example, Eisenberg et al.9) measured the dissolution rate of
a cylinder made by benzoic acid in a water–glycerin solu-
tion. They found that the mass transfer coefficient in their
experiment satisfied the dimensionless correlation shown in
Eq. (14).
\[
\frac{k}{U} Sc^{0.644} = 0.0791 Re^{-0.3}
\]
(835 < Sc < 1100, 150 < Re < 5.2 \times 10^4)

where \(U\) is the relative velocity (m/s), \(Re\) is the Reynolds
number (= \(LU\rho_m/\mu\)), and \(Sc\) is the Schmidt number (= \(\mu/\rho_mD\)). In \(Re\) and \(Sc\), \(L\) is the characteristic length (m), \(\mu\) is
the viscosity of molten steel (Pa s), and \(D\) is diffusivity (m^2/s).

Isobe et al.10) investigated the dissolution behavior of a
cylinder made by carbon steel into hot metal. They found
that the mass transfer coefficient in their experiment satis-
ﬁed the following equation.

\[
k \left( \frac{L}{D} \right) = 0.163 Re^{0.78} Sc^{-0.356}
\]

On the other hand, the mass transfer coefficient in the
boundary layer of liquid flowing in a direction parallel to the
plate can be described in Eq. (16).11)

\[
k \left( \frac{L}{D} \right) = \alpha Re^{1/2} Sc^{1/3}
\]

The relationship between the Reynolds number and mass
transfer coefﬁcient in this experiment is shown in Fig. 15.

Table 5. Calculated mass transfer coefﬁcient of Mg in Fe–
0.3 mass% Al molten steel.

<table>
<thead>
<tr>
<th>0.3 mass% Al</th>
<th>100 rpm</th>
<th>200 rpm</th>
<th>400 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass transfer coefﬁcient (cm/s)</td>
<td>0.0068</td>
<td>0.0112</td>
<td>0.0128</td>
</tr>
</tbody>
</table>

Fig. 15. Relationship between the mass transfer coefﬁcient and
Reynolds number for Fe–0.3% Al molten steel.

In this calculation, the characteristic length was assumed to
be the diameter of the MgO rod. As shown in Fig. 15, the
good relationship between the mass transfer coefﬁcient and
\(Re^{0.46}\) was clariﬁed, and this relationship was very close to
Eq. (16). Figure 16 shows a comparison of the experimental
results with the results calculated by Eq. (16). Based on this
result, the value of “\(\alpha\)” in Eq. (16) was estimated to be 1.3.

3.3. Reaction of MgO in Slag with Molten Steel Deoxi-
dized by Al

3.3.1. Experimental Results

Figure 17 shows the composition change in Al, Mg, Ca,
and O in the metal. After deoxidation, the Al content rapidly
increased and then decreased gradually. Mg content
increased in the ﬁrst 5 min after deoxidation and became
nearly constant. Ca content rapidly increased after deoxida-
tion and decreased drastically. After 10 min, the Ca content
was very low. The O content decreased to about 10 ppm
after deoxidation and became around 4 ppm.

3.3.2. Discussion about the Reaction between Molten
Steel and Slag

The increase in the Mg content was discussed by the ther-
modynamic calculation. In this experiment, the activity of O
was calculated using the equilibrium relationship of Al and
Al2O3, assuming that the activity of Al2O3 was unity. Then,
the Mg content equilibrated with O can be calculated by
eqs. (17) and (18).

\[
\Delta G^0_{\text{(10)}} = -89996.98 - 81.95 T \text{ J/mol} \quad (18)
\]

In this calculation, the activity of MgO was unity because
the slag was saturated with solid MgO. From these calcu-
lations, the relationship between Al and Mg content in the
steel was obtained, as shown in Fig. 18. In this ﬁgure, the
contents of Al and Mg at each experimental time are plotted
for the cases of deoxidization by Fe–Al alloy and pure Al.
The calculation results were in good agreement with the
experimental results. Therefore, it can be concluded that the
Mg content was determined by the equilibrium relationship
with the MgO in slag.

Table 5. Calculated mass transfer coefﬁcient of Mg in Fe–
0.3 mass% Al molten steel.
Because of the reaction between molten steel and MgO in slag, the Mg content was higher than that from the reaction between molten steel and MgO rod. In the case of the reaction with slag, Mg is equilibrated with MgO activity in slag; however, in the case of the reaction with the MgO rod, Mg is equilibrated with the spinel formed at the interface. In addition, the Mg content in the case of reaction with slag was always close to equilibrium. Therefore, the reaction rate in this case can be considered to be faster than the dissolution rate of the MgO rod, which was controlled by the mass transfer in the metal phase.

4. Conclusions

In this study, the inclusion composition of Al-deoxidized steel melted in a MgO crucible and the influence of slag were investigated. Then, the mass transfer rates of Mg from the MgO rod to Al-deoxidized molten steel were measured, and the empirical equation was established. Finally, the behavior of Mg based on the reaction between molten steel and the MgO rod was compared to that of the reaction between molten steel and MgO in slag. The following results were obtained.

1) The alumina-type inclusion, which was observed just after Al addition, changed to the spinel-type inclusions regardless of the existence of slag. It was clear that the Mg dissolved in the molten steel, and the spinel formed from the reaction between molten steel and slag and also between molten steel and MgO refractory.

2) The dissolution rate of Mg from the MgO rod increased as the rotation rate and Al content in steel increased. At the interface between the metal and MgO rod, a MgO·Al2O3 spinel layer was formed. According to thermodynamic calculations, Mg and Al in molten steel were considered to be in equilibrium with the spinel layer.

3) The mass transfer coefficient of Mg in this experiment could be expressed by the following dimensionless correlation equation.

\[ k \left( \frac{L}{D} \right) = 1.3 \text{Re}^{1/2} \text{Sc}^{1/3} \]

4) The Mg content was higher for the reaction between molten steel and MgO in slag compared to the reaction between molten steel and MgO rods, as it equilibrated with MgO in slag.

REFERENCES