Dissolution Rate of $\text{Al}_2\text{O}_3$ into Molten $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ Slags

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The dissolution rate of $\text{Al}_2\text{O}_3$ into the $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ slag system was investigated at 1,873 K by employing a novel experimental method which involved continual measurement of the torque variation on a rotating alumina rod dipped into a molten slag. Measured torque variation was successfully related to the dissolution rate of the rod. The dissolution rate of alumina was found affected by a number of factors: the rate increased with increasing temperature, the rotating speed of the rod, the $\text{CaO}$ content in the slag, and the $\text{Al}_2\text{O}_3$ content in the slag for a fixed $\text{CaO}$ content. It was found that the dissolution rate was highly dependent on the viscosity and the diffusivity of slags. The activation energy obtained from an Arrhenius type analysis was in the range of 84 kJ mol$^{-1}$. It was concluded that the dissolution of $\text{Al}_2\text{O}_3$ into the $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ slag system was controlled by the mass transfer in the slag phase. An iso-dissolution rate diagram was constructed for the dissolution of $\text{Al}_2\text{O}_3$ into the $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ slag system at 1,873 K.

KEY WORDS: dissolution; rate; alumina; $\text{Al}_2\text{O}_3$; $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$; slag.

1. Introduction

The non-metallic inclusions are formed in the steelmaking process by deoxidation. The presence of non-metallic inclusions gives rise to various problems in steelmaking process and steel products. In most steel grades, therefore, inclusions should be removed as much as possible before casting. Once arrived at the metal/slag interface, the inclusions are desired to attach themselves firmly to the slag phase and then quickly dissolve into the slag. If the inclusion is not completely absorbed to slag phase, the inclusion staying at the slag/steel interface makes a role of steric hindrance on inclusion absorption and it can be re-entrapped into the steel phase by steel stream. For the purpose of inclusion removal, therefore, the slag should satisfy two basic requirements, i.e., high wettability with inclusions and high dissolution rate of inclusions into the slag.

Many works$^{1–10}$ have been carried out on the dissolution of alumina into slags focused on the clarification of dissolution mechanism. If there is no compound formation at the alumina slag interface, the dissolution of alumina is controlled by the mass transfer in the boundary layer of slag.$^{1,2)}$ Under certain conditions, however, the dense compound layer such as $\text{CaO}–6\text{Al}_2\text{O}_3$ and $\text{MgO}–\text{Al}_2\text{O}_3$ is formed at the alumina slag interface.$^{1,3–7,10)}$ If this is the case, some investigators$^{3–7)}$ suggested that the dissolution of alumina is controlled by the diffusion in the solid compound. Nakashima et al.$^{1)}$ reported that no compound formation at the alumina slag interface was observed for $\text{Na}_2\text{O}–\text{SiO}_2$ slag system (1,373–1,673 K), and that the dissolution of alumina is controlled by the slag phase mass transfer. Sridar$^{2)}$ observed the dissolution of alumina into slag in situ with a confocal scanning laser microscope. They$^{2)}$ reported that the dissolution of alumina particle was controlled by boundary layer diffusion. Sandhage et al.$^{3,4)}$ reported that when the alumina dissolved into $\text{MgO}–\text{Al}_2\text{O}_3$ containing $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ slag, the $\text{MgO}–\text{Al}_2\text{O}_3$ spinel layer was formed at the alumina/slag interface, and the dissolution rate decreased with increasing $\text{MgO}$ content. With the support of kinetic data and microprobe data, they discussed the kinetics of spinel formation which includes simultaneous dissolution and formation of spinel. However the formation and the layer thickness of $\text{MgO}–\text{Al}_2\text{O}_3$ spinel depends on the slag composition, temperature, and flow condition.$^{3,4,7)}$

As described above, many works have been carried out in view of elucidating the dissolution mechanism, and each of them has been studied at different temperatures and slag compositions. Hence, none of them has suggested the dissolution rates into liquid slag in the wider compositional range, even in $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ system which is a basic slag system in the steelmaking process. In addition, the factors affecting on the dissolution of alumina such as viscosity, diffusivity and composition have not been clearly understood.

In the present study, the dissolution rate of an alumina inclusion into slags was experimentally determined by employing a novel experimental technique which involves measurement of torque change in the system of an alumina rod rotating in a molten slag pool. In addition, the iso-dissolution rate diagram was constructed for the dissolution of alumina into $\text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3$ slag at 1,873 K.
2. Experimental

2.1. Materials

Slags were first prepared by mixing high purity oxides (Al₂O₃, SiO₂ and CaO) at an appropriate proportion and melted in a graphite crucible at 1873 K using a high frequency induction furnace. Slags for the present study are given in Fig. 1 and Table 1. The slag composition was determined by XRF analysis.

Alumina rod having a cylinder shape (8\(\times\)10\(^{-3}\) m D \(\times\) 10\(^{-3}\) m L) was prepared by sintering high purity Al₂O₃ (\(\geq 99.8\%\)).

2.2. Experimental Apparatus

The apparatus employed in the present study to measure the dissolution rate of alumina is schematically shown in Fig. 2. A resistance furnace was used for heating, and the temperature was kept at 1873 K for most experiments. The entire reaction part was enclosed in an alumina tube (70\(\times\)10\(^{-3}\) m ID \(\times\) 10\(^{-3}\) m L), both ends of which were closed using a water-cooled brass end cap (upper end) and a silicon rubber stopper (lower end), respectively. The inside of the tube was kept flushed with argon gas. The graphite crucible (50\(\times\)10\(^{-3}\) m ID \(\times\) 80\(\times\)10\(^{-3}\) m L) filled with 180 g of a slag was preheated at above the uniform temperature zone by holding it using a molybdenum wire. It was then lowered to the zone, and placed on the support. After the complete melting of the slag sample, the cylindrical alumina rod suspended to a torque measuring device (Brookfield LVDV-III\(^{16}\)) using a molybdenum ring chain was dipped into the molten slag. Immediately after dipping, the alumina rod was rotated at a given rpm by turning on the torque measuring device. The change of torque on the alumina rod was continuously measured and recorded in a computer. In order to identify the relationship between the torque change and the dimensional change of the rod by dissolution, some runs were interrupted after a predetermined length of time, and the alumina rods were removed from the molten slag and dimensional changes were measured.

3. Development of a Novel Experimental Technique

A novel method for measurement of the dissolution rate of a solid cylindrical rod into a liquid was developed and employed in the present study. The method was unique in that it made use of the fact that the change in torque is directly related to the change in the rod geometry, which in turn is related to the dissolution rate of the rod. A cold model study was preceded in order to determine a quantitative relationship between the torque and rod diameter for the present system geometry. Then, applicability of the relationship to the system of an alumina rod dissolving in a slag was considered.

3.1. Cold Model Study

Cold model experiments were carried out using silicon oil of different viscosities (0.985 P and 4.92 P at 298 K) and aluminum rods of various diameters and dipping lengths (3–8\(\times\)10\(^{-3}\) m in diameter and 20–50\(\times\)10\(^{-3}\) m in dipping length). Figure 3 shows the relationships between torque and rod diameter at different rotating speeds. It is clearly seen that the torque on the rod is linearly proportional to the square of the rod diameter for a given rotating speed and liquid viscosity. Figure 4 shows the change of the torque by

Table 1. Investigated slag compositions.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Run No.</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
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<td>0.0</td>
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<td>D1</td>
<td>49.6</td>
<td>19.9</td>
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<td>48.1</td>
<td>D2</td>
<td>37.2</td>
<td>24.8</td>
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<td>D3</td>
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<td>E1</td>
<td>45.6</td>
<td>25.3</td>
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<td>46.0</td>
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<td>I2</td>
<td>45.1</td>
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Fig. 1. Investigated slag compositions.

Fig. 2. Experimental apparatus.

Fig. 3. Graph showing the relationship between torque and rod diameter.

Fig. 4. Graph showing the change of torque by cold model study.
changing the dipping length of the rod into the slag. The torque is seen to be linearly proportional to the dipping length. Combination of these two observations results in the following relationship:

$$\frac{\tau_1}{\tau_2} = \left(\frac{d_1}{d_2}\right)^2 \left(\frac{h_1}{h_2}\right)$$ ..............................................(1)

where \(\tau_i\) is the torque when the rod of diameter \(d_i\) and in dipped length of \(h_i\) rotates at a given rotating speed.

Applying Eq. (1) to the system similar to that of the present study, one can obtain the following equation (Eq. (2)):

$$d_i = d_o \left[\left(\frac{\tau_i}{\tau_o}\right)^{1/2} \left(\frac{h_o}{h_i}\right)\right]$$ ..............................................(2)

where subscripts \(o\) and \(t\) represent values at initial time and at time \(t\), respectively.

Sanghage et al. measured a length change of alumina by the rotating rod method, and reported that decrease in the dipping length due to dissolution was linearly proportional to the elapsed time. This observation may be summarized by the following equation:

$$h_t = h_o - \frac{h_t - h_i}{t_R} t$$ ..............................................(3)

where \(t_R\) is the total reaction time, \(h_t\) and is the dipped length after time \(t_R\).

Combining Eqs. (2) and (3), one can obtain Eq. (4) given in the following:

$$d_i = d_o \left[\left(\frac{\tau_i}{\tau_o}\right)^{1/2} \left(1 - \frac{h_t}{h_o} \left(\frac{t}{t_R}\right)\right)^{-1/2}\right]$$ ..............................................(4)

Equation (4) enables to estimate the instantaneous diameter of the rod at a time \(t\). Alternatively, one can apply Eq. (1) to estimate the instantaneous mass of the rod during dissolution:

$$\frac{\tau_i}{\tau_o} = \frac{d_i^2 h_i}{d_o^2 h_o} = \frac{w_t}{w_o}$$ ..............................................(5)

where \(w_o\) and \(w_t\) are the masses of the dipped portion of a rod at the initial time and at a time \(t\), respectively.

The amount of alumina dissolved for the length of a time \(t\) is then given by the following equation, Eq. (6):

$$\Delta w = w_o \left(1 - \frac{\tau_i}{\tau_o}\right)$$ ..............................................(6)

Now, Eqs. (5) and (6) enable to estimate the change in the mass of the rod due to dissolution simply by measuring the change in torque.

### 3.2. Applicability

In order to ascertain the validity of the new method described in the above, a series of experiments were carried out by the present new method and by the typical conventional method, which involved quenching and weighing of the rod or measuring diameter change of the rod at a number of time intervals. The results are given in Fig. 5, in which the fractional change in torque measured by the new method is compared with the fractional mass changes for different dissolution times measured by the conventional method. It is remarkable that the fractional torque changes measured by the new method are in excellent agreement with those measured by the conventional method. This agreement is a solid evidence that Eq. (5) does hold for the system of the present study, and hence confirms the validity of the present new method for measuring the dissolution rate of an alumina rod in a liquid slag.

## 4. Results and Discussion

Figure 6 shows a typical result of an experimental run under a given experimental condition. It is seen that the torque decreases continually with time, which is due to the change in the geometry of the rod by dissolution. The change with time of the diameter, dipping length and mass of the rod can readily be estimated from this information of the torque change using Eqs. (3)–(6), and the results are given in Fig. 7. Values of \(h_t\) used in the equations were obtained from measurement after individual experimental runs.

### 4.1. Effect of Rotating Speed

Figures 8(a) and 8(b) show the effect of rotating speed of the rod on the dissolution rate for two different slag compositions (A2: 51.9%CaO–48.1%Al2O3 and C3: 48.6%CaO–13.1%SiO2–38.3%Al2O3 in mass%). It is clear that the dis-
The solution rate increases with increasing the rotating speed. Figure 9 shows the relationship between the dissolution rate ($-\frac{dr}{dt}$) and the rotating speed represented by the periphery velocity ($u$). In this comparison values at the initial stage were used. It is seen that the logarithm of the dissolution rate of alumina is linearly proportional to the logarithm of the rotating speed with the slope of 0.7. Eisenberg et al. have also reported a similar finding. The fact that the dissolution rate increases with increasing the rotating speed implies that dissolution of alumina into slag is controlled by the slag phase mass transfer, partly at least. They proposed...
the following equation for the mass transfer coefficient in
the slag phase, which takes into account the effect of the ro-
tating speed of the rod:

\[ k = C \cdot Sc^{-0.644} \left( \frac{d}{v} \right)^{-0.3} u^{0.7} \] ....(7)

where \( k \) is the mass transfer coefficient (m/s), \( C \) a con-
stant, Sc Schmidt number (= \( v/D \)), \( D \) diffusivity (m²/s), \( d \)
cylinder diameter (m), \( v \) kinematic viscosity of liquid
(m²/s), and \( u \) peripheral velocity (m/s).

Looking at the slag side, the flux of \( \text{Al}_2\text{O}_3 \) \( (J_{\text{Al}_2\text{O}_3}) \) can be
expressed by Eq. (8):

\[ J_{\text{Al}_2\text{O}_3} = k(C_{\text{Al}_2\text{O}_3}^s - C_{\text{Al}_2\text{O}_3}^b) \] ....(8)

where \( J_{\text{Al}_2\text{O}_3} \) is the flux of \( \text{Al}_2\text{O}_3 \) in the slag phase per unit
area and unit time (kg·m⁻²·s⁻¹), \( C_{\text{Al}_2\text{O}_3}^s \) and \( C_{\text{Al}_2\text{O}_3}^b \) are the
concentrations (kg·m⁻³) of \( \text{Al}_2\text{O}_3 \) at the interface and in
the bulk, respectively.

Combining the mass balance for \( \text{Al}_2\text{O}_3 \), one can obtain
Eq. (9) given below.

\[ \rho_{\text{Al}_2\text{O}_3} \cdot A \cdot \frac{dr}{dt} = A \cdot J_{\text{Al}_2\text{O}_3} \] ....(9)

where \( A \) is the surface area reacting with slag (m²), \( \rho_{\text{Al}_2\text{O}_3} \)
the density of \( \text{Al}_2\text{O}_3 \) (kg·m⁻³) and \( r \) the radius of rod (m).

Combination of Eqs. (8) and (9) yields,

\[ R_d = \frac{dr}{dt} = k \left( \frac{\rho_{\text{slag}}}{100 \rho_{\text{Al}_2\text{O}_3}} \right) [(mass\% \text{Al}_2\text{O}_3)_s - (mass\% \text{Al}_2\text{O}_3)_b] \] ....(10)

where \( R_d \) is the dissolution rate (m/s), \( \rho_{\text{slag}} \) is the
mass density of the bulk slag (kg·m⁻³), and \( (mass\% \text{Al}_2\text{O}_3)_s \) and
\( (mass\% \text{Al}_2\text{O}_3)_b \) are the mass% of \( \text{Al}_2\text{O}_3 \) at the interface and
in the bulk, respectively. \( (mass\% \text{Al}_2\text{O}_3)_b \) is liquidus concen-
tration assuming local equilibrium with solid alumina.

Equation (10), with help of Eq. (7), clearly indicates that
the dissolution rate \( (R_d) \) should be proportional to the rotat-
ing speed of the rod to the power of 0.7, which indeed is the
case in the present study. In Eq. (10), the mass transfer co-
efficient \( (k) \) is the only term that is affected by the rotating
speed of the rod. Thus the following relationship of Eq.
(11) must hold:

\[ \left( \frac{R_{d1}^{\text{slag}}}{R_{d2}^{\text{slag}}} \right)_{u_1} = \left( \frac{R_{d1}^{\text{slag}}}{R_{d2}^{\text{slag}}} \right)_{u_2} \] ....(11)

where \( R_{d1}^{\text{slag}} \) and \( R_{d2}^{\text{slag}} \) are dissolution rates of slag 1 and
slag 2, respectively, and \( u_1 \) and \( u_2 \) represent two different
rotating speeds. Equation (11), which indicates the ratio of
the dissolution rate of two different slags being indepen-
dence of the rotating speed, facilitates conversion of the dis-
solution rate at one rotating speed to that at another rotating
speed.

4.2. Effect of Temperature

Figure 10 shows the effect of temperature on the dissolu-
tion rate of alumina into slag. It is seen that the dissolution rate
of alumina increases with increasing temperature. Figure 11
shows the effect of temperature on the mass transfer coefficient,
avuming that the dissolution is con-
trolled by the mass transfer in the slag phase and hence
Eq. (10) applies. The activation energy of the mass transfer
in the slag phase obtained by the Arrhenius type analysis is
found to be 84 kJ·mol⁻¹ for slag A2 (51.9%CaO–
48.1%Al₂O₃ in mass%). Taking into consideration the fact
that the expression for the mass transfer coefficient given
by Eq. (7) includes diffusivity and viscosity terms, both of
which are temperature dependent, the activation energy of
the mass transfer in the slag phase may be considered to
consistent of the contribution from both viscosity and diffusiv-
ity in the slag phase. The effect of temperature on each of
these terms may be represented by the Arrhenius type ex-
pression

\[ D = D_o \exp(-\Delta E_D/RT) \] ....(12)

\[ \mu = \mu_o \exp(\Delta E_\mu/RT) \] ....(13)

\[ k = k_o \exp(-\Delta E_k/RT) \] ....(14)

where \( D \) is the diffusivity, \( \mu \) the viscosity, \( k \) the mass trans-
fer coefficient, \( \Delta E_D \) the activation energy for the corre-
sponding term, and \( D_o, \mu_o, \) and \( k_o \) are constants.

Combination of Eqs. (7) and (12)–(14) results in the fol-
lowing relationship among the activation energies of the
mass transfer coefficient (\( \Delta E_k \)), diffusion (\( \Delta E_D \)) and viscos-

In general, the activation energy of diffusion of Al in the slag phase is in the range of 42–356 kJ·mol⁻¹ and that of viscosity is in the range of 93–121 kJ·mol⁻¹. Substituting these values into Eq. (15) yields that the activation energy for mass transfer coefficient is in the range of 59–271 kJ·mol⁻¹. It is noted that the activation energy of the mass transfer coefficient obtained from the present study (84 kJ·mol⁻¹) falls well in the above range. This agreement is another indication that dissolution of Al₂O₃ into the slag is controlled by the mass transfer in the slag phase.

Table 2 gives the summary of previous works reported in the literature. It can be seen that the activation energy is widely different for different slag systems, but it is still suggested that the mass transfer in the slag phase is rate-controlling.

### 4.3. Effect of Slag Composition

Figure 12 shows the dissolution rate of Al₂O₃ in a number of different slag compositions at 1873 K. It is seen in the figure that the dissolution rate differs several folds for different slag compositions. The highest dissolution rate occurs in the CaO–Al₂O₃ binary slag at CaO saturation. General trend is that the dissolution rate increases with increasing CaO content for a fixed SiO₂/Al₂O₃ ratio and increasing Al₂O₃ content for a fixed CaO content, as seen in Fig. 13.

When a liquid slag comes into contact with solid Al₂O₃, a new phase might form at the interface, depending on the slag composition (see Fig. 14). For example, when a liquid slag A in Fig. 14 is allowed to contact with Al₂O₃, the phase diagram predicts that the solid CaO·2Al₂O₃ phase will form at the interface due to mutual interaction. If this is the case, the interfacial concentration of Al₂O₃, i.e., [Al₂O₃] in Eq. (10), is the one given by point B, and hence the concentration driving force, i.e., ∆C = ([Al₂O₃] - [Al₂O₃]₀) in Eq. (10), is represented by the length of AB. In order to confirm formation of a new phase at the interface, some specimens were rapidly cooled by taking them out of the heating zone and blowing helium gas. Those specimens were subjected to the SEM-EPMA analysis in the vicinity of the slag–alumina interface. Figure 15 shows the results. These figures confirm formation of CaO·2Al₂O₃ and the binary slag.
CaO·6Al₂O₃ depending on the slag composition. In Eq.
(10) the terms which are affected most by change in the slag
composition are the concentration driving force term,
[(%Al₂O₃)ₙ−(%Al₂O₃)ₘ], and the mass transfer coefficient,
k. In order to determine the importance of each of these
terms, first, the dissolution rate of Al₂O₃ into a number of
different slags is plotted against [(%Al₂O₃)ₙ−(%Al₂O₃)ₘ] in
Fig. 16. Dependence of the dissolution rate on
[(%Al₂O₃)ₙ−(%Al₂O₃)ₘ] is not clearly apparent in the figure.
This may imply that it is the mass transfer coefficient
that is more strongly affected by the slag composition.
Numerical values of the mass transfer coefficient for vari-
ous compositions of the present slag system are not readily
available. From Eq. (7), however, it is seen that the slag
composition affects the mass transfer coefficient through
affecting both viscosity of the slag and diffusivity of Al₂O₃
(or Al³⁺) in the slag. Viscosity values of the slag in the pre-
sent study have been reported in the literature as given in
Fig. 17. Diffusivity information on the present slag sys-
tem is scarce. Henderson et al. studied self-diffusivities
of aluminum in CaO–SiO₂–Al₂O₃ slag at two different
compositions in the temperature range of 1 673–1 793 K,
and reported the following relationships:

For 43.5%CaO–46.5%SiO₂–10%Al₂O₃ in mass%,
\[
D = (4.3 \pm 0.3) \exp \left[ -\frac{356 000 \pm 73 000}{RT} \right]
\]  \hspace{1cm} \text{(16)}

For 38.6%CaO–41.4%SiO₂–20%Al₂O₃ in mass%,
\[
D = (5.4 \pm 0.2) \exp \left[ -\frac{251 000 \pm 42 000}{RT} \right]
\]  \hspace{1cm} \text{(17)}

where \(D\) is the diffusivity of aluminum in the slag (m²·s⁻¹),
and \(R\) is the gas constant (8.314 J·mol⁻¹·K⁻¹).

The diffusivity information given above is not sufficient
to evaluate the mass transfer coefficient using Eq. (7), but
the above information enables us to determine the inter-re-
lation between diffusivity and viscosity, knowing that
viscosity also varies with temperature. Using Eqs. (16) and
(17) together with viscosities reported in the literature, the
dependency of the diffusivity on the viscosity of the CaO–
SiO₂–Al₂O₃ slag system was examined for two different
slag compositions at 1 873 K, and the results are given in
Fig. 18. Although data points are not enough to draw a
definitive conclusion, it is clear that the diffusivity has a
strong dependency on the viscosity for the present slag sys-
tem, \(D \propto \mu^{3.22}\). Taking this correlation into account,
one can deduce from Eq. (7) that the mass transfer coeffi-
cient, \(k\), should be proportional to the viscosity to the power
of −3.06. It is now clear that the mass transfer coefficient

\[
D = \frac{RT}{54 02 251000 42 000 \exp \left[ \frac{\Delta H + \Delta S}{RT} \right]}
\]  \hspace{1cm} \text{(16)}

\[
D = \frac{RT}{43 03 356 000 73 000 \exp \left[ \frac{\Delta H + \Delta S}{RT} \right]}
\]  \hspace{1cm} \text{(17)}

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Fig. 14. Isothermal phase diagram of CaO–SiO₂–Al₂O₃ system
indicated are primary phases to form when liquid slags
are in contact with solid Al₂O₃.
(CA₂: CaO·2Al₂O₃, CA₆: CaO·6Al₂O₃, A₃S₂: 3Al₂O₃·2SiO₂)

Fig. 15. Observation at the alumina/slag interface.
(a) Slag C2: 54.7%CaO–11.6%SiO₂–33.7%Al₂O₃ in mass%.
(b) Slag C4: 42.6%CaO–14.6%SiO₂–42.8%Al₂O₃ in mass%.
The concentrational driving force \( \left( \frac{\% \text{Al}_2\text{O}_3}{\% \text{H}_{11002}} \right) \) and the mass transfer coefficient \( \left( \frac{\% \text{Al}_2\text{O}_3}{\% \mu} \right) \) are the two terms in Eq. (10) which are affected most by the composition of the slag. The mass transfer coefficient is in turn strongly influenced by the viscosity, as mentioned above. Taking these discussions into consideration, the dissolution rates of the alumina rod are plotted against \( \left( \frac{\% \text{Al}_2\text{O}_3}{\% \mu} \right) \) in Fig. 19. Much better linear relationship is evident in this figure than in Fig. 16 where the dissolution rate is related against the concentrational driving force \( \left( \frac{\% \text{Al}_2\text{O}_3}{\% \mu} \right) \) alone.

4.4. Relative Dissolution Rate Diagram

It has been seen in the earlier sections that the dissolution rate of \( \text{Al}_2\text{O}_3 \) in the \( \text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3 \) slag system is dependent on various factors including the composition and viscosity of the slag, and the rotating speed of the alumina rod. It would be of use if dissolution rates of \( \text{Al}_2\text{O}_3 \) under different conditions could be expressed relative to the one under a reference condition. Those numerical values of the dissolution rate given in Fig. 12 in the earlier section are valid in fact only for the system geometry employed in the present study and the rotating speed of 150 rpm. If relative ratios of these values in the figure are taken, however, these ratios must be independent of the system geometry and the rotating speed owing to the relationship given in Eq. (11). Figure 20 is the relative iso-dissolution rate diagram for \( \text{Al}_2\text{O}_3 \) in \( \text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3 \) slag.

### Fig. 16
Dependence of the dissolution rate of \( \text{Al}_2\text{O}_3 \) into slag on the concentrational driving force of \( \left( \% \text{Al}_2\text{O}_3 \right) \).

### Fig. 17
Iso-viscosity diagram (poise) of \( \text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3 \) system at 1873 K.13)

### Fig. 18
Dependency of the diffusivity on the viscosity of \( \text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3 \) slag system at 1873 K.

### Fig. 19
Combined effect of the concentrational driving force and the physical properties of the slag (\( D \) and \( \mu \)) on the alumina dissolution rate.

### Fig. 20
Relative iso-dissolution rate diagram of \( \text{Al}_2\text{O}_3 \) in \( \text{CaO}–\text{SiO}_2–\text{Al}_2\text{O}_3 \) slag.
(Reference composition: 57.7%CaO (Sat.)–42.3%Al\text{2O}_3 in mass%)
the slag for a fixed CaO/SiO₂ ratio, but the effect of Al₂O₃ is not as strong as that of CaO. It is of interest to notice that the iso-dissolution rate lines in Fig. 20 show a similar trend to the iso-viscosity lines in Fig. 17. This suggests that the viscosity, which influences the mass transfer coefficient \( k \) in Eq. (10), plays a major role in the dissolution of Al₂O₃ in the slag. It should be noted however that the viscosity term shown in Fig. 19 represents the combined effect on the mass transfer coefficient of both direct influence of viscosity and its indirect influence via diffusivity.

5. Conclusions

Dissolution kinetics of Al₂O₃ into CaO–SiO₂–Al₂O₃ slags was studied at 1 873 K by employing a novel method which involved rotation of an alumina rod dipped in a molten slag pool and measurement of the change in torque due to dissolution during rotation. The findings are summarized in the following:

1. The dissolution rate increases with temperature and the rotating speed.
2. The dissolution rate increases with increasing CaO content and with decreasing Al₂O₃ content for a fixed CaO/SiO₂ ratio.
3. Viscosity of the slag has a strong negative influence on the dissolution rate of Al₂O₃. This influence comes partly by an indirect manner, viz., the dissolution rate is positively influenced by diffusivity which in turn negatively affected by viscosity.
4. It is proposed that the dissolution of Al₂O₃ into CaO–SiO₂–Al₂O₃ slag is controlled by the mass transfer in the slag phase. The activation energy of the mass transfer coefficient was found to be in the range of 84 kJ·mol⁻¹.
5. The iso-dissolution rate diagram for Al₂O₃ is constructed for CaO–SiO₂–Al₂O₃ slag system, which can be used for a quantitative comparison of slags of different compositions for their effectiveness on Al₂O₃ dissolution.

REFERENCES