Flux Film in the Mold of High Speed Continuous Casting

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The film, which is formed by mold flux in the continuous casting mold, plays very important roles in terms of lubrication or heat transfer. However, the thickness or structure of it has not been adequately clarified.

In this study, the sample of actual flux film was taken from the continuous casting mold just after the cast, keeping its position as it was during the cast. Thanks to this trial, thickness of the flux film at the meniscus in the mold could be clarified. According to the observation on the flux film section by microscope, the structure of the flux film was discussed, in terms of its crystallization.

Furthermore, based on the results of the observation mentioned above, the heat transfer phenomenon through the flux film in the mold was discussed.

As a result of the discussion, the following conclusions were obtained.

1) The mold flux film can be considered to be about 1 mm. Glassy layer, which has been considered to be molten flux on the top of molten steel during the cast and covered the film just after the cast, can be assumed to make up the film during the cast.

2) The liquid layer in the film is as thick as that is estimated on the basis of mold flux consumption during the cast.

3) In the case that the film at the meniscus in the mold is about 1 mm thick, total thermal resistance of radiation and conduction is equivalent to interfacial thermal resistance between the film and the mold.

4) The reported values of interfacial thermal resistance can be considered to be larger than that in the actual mold during the casting. The reason seems to be that they were measured in conditions without any pressure by the molten steel, like that in the mold. In the actual mold, the interfacial thermal resistance seems to be smaller.

KEY WORDS: continuous casting; mold flux; film; crystallization; meniscus, interfacial thermal resistance; consumption.

1. Introduction

Mold flux film at the meniscus in the continuous casting mold plays important roles in terms of lubrication and heat transfer. In this study, its thickness and behavior on the heat transformation was discussed.

The authors reported various values about the thickness of the mold flux film. After the 1980’s, numerical simulation about lubrication or infiltration came to be conducted for high speed continuous casting, and at that time, the thickness of the film was considered as a necessary parameter for the calculation.1–3) The values were estimated from consumption of mold flux during casting and to be about 0.05–0.2 mm. In these estimations, there remained a problem that the whole film consists of only liquid layer and the existence of solid layer was not taken into consideration.

Later, it was reported that there is the hysteretic phenomenon of heat transfer in the mold and the crystallization of cuspidine (Ca$_4$Si$_2$O$_7$F$_2$) or its resolving into liquid phase are concerned.4) Then, a medium of heat transfer came to be considered as a new function of the film. In that report, the thickness of the film was considered to be about 2 mm, and it includes the solid layer of 0.6 mm thickness, which stays in the mold in spite of infiltration of liquid layer.

Furthermore, mild cooling of solidified shell with the crystallization of the film was found to be effective for prevention of longitudinal cracking on the surface of hypoperitectic steel slabs.5) Considering this effect, various researches and analyses on the heat transfer were reported.6–8) But the thickness of the film was considered to be 0.2–0.4 mm, comparatively smaller.

In this way, thickness of the mold flux film is very important factor considering each phenomenon in the continuous casting mold, but the thickness has been varied by the reports and it has not been clarified yet.

The authors previously reported high speed casting of hypoperitectic steel slabs at 5.0 m/min and prevention of the longitudinal cracking by mild cooling with crystallization in the mold flux.9) In that report, samples of mold flux film taken out of the mold were investigated and the influence of mold flux composition to crystallization of cuspidine was discussed.

In this study, the film was researched in more detail and the mechanism of heat transfer through the film is dis-
2. Methods

2.1. Casting Conditions

Casts were conducted with a pilot caster of medium-thick slab in Kashima steel works in this study. Its vertical length, radius of curvature and total metallurgical length was 1.5 m, 3.5 m and 12.8 m, respectively. The mold size was 1 000 mm wide and 90 mm thick.

Eighty tons of molten steel was prepared for the casts. The contents of alloying elements are listed in Table 1. The steel grade was hypoperitectic and carbon content was 0.09–0.12 mass%.

Two kinds of mold flux were used for the casts. These were the mold flux “B” and “C” in the previous paper. The flux B has conventional composition for the cast of hypoperitectic steel. On the other hand, the composition of the flux C was in the primary crystallization field of cuspidine, therefore it was closer to cuspidine than that of the flux B. Main specifications of the flux are listed in Table 2. Their basicity of T.CaO/SiO₂ were 1.5 and 1.8, their solidification temperatures were 1 496 K and 1 509 K and their viscosities at 1 573 K were 0.06 Pa·s and 0.04 Pa·s.

2.2. Mold Flux Consumption

Mold flux consumption during the cast was evaluated. Under the state of constant casting speed, the weight of mold flux provided into the mold was measured and the value was calculated into the consumption per unit surface area of the slabs.

2.3. Sampling of Mold Flux Film

The sampling method of the film in this study is shown in Figs. 1 and 2. Before the beginning of the cast, stainless steel wire was set at the meniscus in the mold. At the beginning, mold flux began to be provided into the mold after the rise of the molten steel surface up to the position of the wire. The flux formed rim adhering the wire during the cast. After the cast, the whole a rim with the wire was taken out of the mold. The meniscus level for the rim was identified by comparing it with the position of molten steel surface in the mold measured by immersion of steel wire.

The rim was molded into resin and its vertical section was polished for observation by optical microscope.

3. Results

3.1. Cast

Trends of the cast are shown in Fig. 3. This is an example of the cast with mold flux C. Casting speed, set at 2.0 m/min just after the start of the cast, was raised to 3.0 m/min and 3.5 m/min in that order. During the cast, surface level of molten steel was constantly controlled within error of 5 mm.

At the end of the cast, casting speed was decreased to 0.3 m/min and the feeding of molten steel into the mold was stopped. In this state, the falling speed of the molten steel surface was about 0.6 m/min and it was faster than that of withdrawal of solidified shell.
3.2. Mold Flux Consumption

Relation between mold flux consumption and casting speed is shown in Fig. 4. The consumption decreased with the increase of casting speed. It did not differ by mold flux.

3.3. Structure of Mold Flux Film

Overview of the rim of mold flux C is shown in Fig. 5. It was taken after the cast mentioned above. This figure shows the inner surface contacting with solidified shell in the mold. Sintered particles and molten droplets existed on its surface and these are considered to adhere after the cast.

The vertical section of that film is shown in Fig. 6. The meniscus level in the mold was identified as a broken line in the figure. Here, the surface of molten steel fluctuated continuously, so this identified level is considered to be the highest in the fluctuation.

The two frames in the Fig. 6 are lower than 8 mm or 15 mm than the meniscus level. In the frame 15 mm below the meniscus, the film became partially thick. The reason for this is adhesion of molten droplet after the cast.

The section at 8 mm below the meniscus is magnified and shown in Fig. 7. At this point, fine crystal phase of several hundreds μm thickness exists along the outer surface (mold side), and columnar crystal phase inside. Furthermore, fine crystal phase of about 50 μm thickness existed along the inner surface (solidified shell side). As will be mentioned later, this phase can be considered to be liquid phase at the cast.

This structure continued downward in the same way.

The section at 15 mm below the meniscus is magnified and shown in Fig. 8. The same structure as shown in Fig. 7 exists in the left side of broken line. On the other hand, fine crystal phase spreads toward the molten droplet in the right side of the broken line.

The structure of the film at 8 mm below the meniscus is shown in Fig. 9 for mold flux B. As well as the case of mold flux C, fine crystal phase of 0.2–0.3 mm thickness lied along the outer surface. But glassy phase exists inside. At this point, a different layer of 50 μm thickness exists along the inner surface.
4. Discussion

4.1. Thickness of Mold Flux Film

On account of the results mentioned above, the authors tried to estimate structure and thickness of the mold flux film during the cast.

4.1.1. Thickness of Liquid Layer

Mold flux consumption shown in Fig. 4 was 0.10–0.15 kg/m² at 3.0–3.5 m/min. Assuming the density of mold flux to be 2.5 kg/m³, the value of consumption is equivalent to the thickness of 40–60 μm, this is within the range reported previously.

Because the structure of molten droplet on the surface of the film included fine crystal phase as shown in Fig. 8, this phase can be considered as liquid phase at the casting state. The reason why this phase did not show glassy phase is considered to be that the composition of the mold flux C was easy to crystallize, because it is quite near cuspidine.

The thickness of fine crystal phase along the inner surface was about 50 μm at 8 mm below the meniscus, and this corresponds to that estimated from consumption.

Thus, the thickness of liquid phase in the film can be estimated precisely by calculation from the consumption. Mold flux consumption decreases with increase of casting speed, as shown in Fig. 4. Taking into consideration that the thickness of the film is about 40–60 μm for casting speed of 3.0–5.0 m/min, the thickness of 50–200 μm, reported previously, is reasonable for common casting speed of 1.0–3.0 m/min.

4.1.2. Total Thickness of the Film

The total area of fine crystal phase and columnar crystal phase outside the liquid phase, shown in Fig. 7 as is the case of mold flux C, can be considered to be solid layer adhering to the mold and exist at the meniscus during the cast. Then, the mold flux film, which is the total of solid and liquid layers, is about 1 mm thick at the meniscus.

In the case of mold flux B, as shown in Fig. 9, at this point, the layer of 50 μm thickness existed at the inner side of the film. According to the analogy of the case of mold flux C, this layer is also considered to be liquid phase during the cast. The glassy phase between the fine crystal phase and the liquid one should be considered to exist during the cast as it is, not to be the liquid phase which adhered after the end of cast.

4.2. Heat Transfer through the Mold Flux Film

4.2.1. Thermal Resistance in the Film

Heat transfer through the mold flux film is schematically shown in Fig. 10. There are two kinds of thermal resistance concerning the film: one is radiation and conduction, and the other is interfacial resistance induced by the roughness of the surface contacting with the mold. They are shown in Eq. (1).

\[
R_{\text{total}} = R_{\text{film}} + R_{\text{int}} = d_{\text{film}}/K_{\text{eff}} + R_{\text{int}}
\] (1)

Here, \(R_{\text{total}}\) is total thermal resistance, \(R_{\text{film}}\) is thermal resistance in the film, \(R_{\text{int}}\) is interfacial thermal resistance, \(d_{\text{film}}\) is thickness of the film, and \(K_{\text{eff}}\) is the apparent heat transfer coefficient.

The values of \(R_{\text{film}}\) and \(R_{\text{int}}\) reported previously are shown in Fig. 11 as a function of mold flux thickness. In most reports, the film is considered to be 0.2–0.3 mm thick, \(R_{\text{int}}\) to be larger than \(R_{\text{film}}\) and to be main factor in \(R_{\text{total}}\).

But, as mentioned above, assuming the film to be 1 mm thick, \(R_{\text{film}}\) comes to be larger than that was considered before, and to be equivalent to \(R_{\text{int}}\).

4.2.2. Interfacial Thermal Resistance

Previously reported values of \(R_{\text{int}}\) is converted to 20–70 μm of the thickness of air gap, assuming the temperature of air gap between the mold and the film to be
500–800 K\(^7\) and quoting thermal conductivity of air in this temperature range.\(^9\) In fact, the film exists under the condition of static pressure from molten steel, so it is hard to consider that such thick air gap exists continuously at the meniscus in the mold during the casting.

Here, an estimation of \(R_{\text{int}}\) is tried on the basis of experimental data\(^9\) and one-dimensional heat transfer computation.

Heat transfer through the film is schematically shown in Fig. 12. Heat flux \(q\), temperature on the interface between solidified shell and the film, \(T_1\), and temperature on the surface of the mold, \(T_2\), are shown in Eq. (2)

\[
q \times (R_{\text{film}} + R_{\text{int}}) = T_1 - T_2 
\]

Equation (3) is derived from Eq. (2).

\[
R_{\text{int}} = \frac{(T_1 - T_2)}{q} - \frac{R_{\text{film}}}{q} = \frac{d_{\text{film}}}{K_{\text{eff}}} 
\]

Thus, if \(T_1\), \(T_2\), \(q\), and \(K_{\text{eff}}\) are given, Eq. (3) expresses linear relation between \(R_{\text{int}}\) and \(d_{\text{film}}\).

\(T_1\) can be obtained from the temperature of the solidifying interface, \(T_{\text{in}}\), thickness of solidified shell, \(d_{\text{shell}}\), solidification coefficient, \(k\), vertical distance from the meniscus to the position of thermocouples in the mold, \(l_{\text{Cu}}\), and thermal conductivity of solidified shell, \(\lambda_{\text{shell}}\).

\[
T_1 = T_0 - \frac{q \times (d_{\text{shell}} / \lambda_{\text{shell}})}{T_0 - q \times (k \times (l_{\text{Cu}} / V_{\text{c}}))^{0.5} / \lambda_{\text{shell}}}) 
\]

On the other hand, \(T_2\) can be obtained from temperature of thermocouples in the mold copper plate, \(T_{\text{Cu}}\), thickness of mold copper plate, \(d_{\text{Cu}}\), thermal conductivity of Cu, \(\lambda_{\text{Cu}}\), as Eq. (5).

\[
T_2 = T_{\text{Cu}} + \frac{q \times (d_{\text{Cu}} / \lambda_{\text{Cu}})}{2} 
\]

By Eqs. (4) and (5), \(T_1\) and \(T_2\) were obtained. Here, \(\lambda_{\text{shell}}\) was assumed to be 33 W/m K\(^6\), \(\lambda_{\text{Cu}}\) to be 385 W/m K\(^7\), \(l_{\text{Cu}}\) to be 0.045 m, \(d_{\text{Cu}}\) to be 0.013 m, \(V_{\text{c}}\) to be 3.5 m/min. The data of \(q\) and \(k\) in the previous paper\(^8\) were used.

Previously reported values about \(K_{\text{eff}}\)\(^7\)-\(^21\) are listed in Table 3. They were evaluated by various methods. Taking them into consideration, 2–3 W/m K was employed as the value of \(K_{\text{eff}}\) in this study.

Relation between \(d_{\text{film}}\) and \(R_{\text{int}}\) expressed by Eq. (3) is shown in Fig. 13. All of the reported values of \(R_{\text{int}}\) are more than 0.4 \times 10\(^{-3}\) m\(^2\) K/W. In the case film is 1 mm thick, as considered in this study, it should be 0.1–0.2 \times 10\(^{-3}\) m\(^2\) K/W.

Many of the previous values were evaluated by the measurement of parallel-plates method.\(^6\)\(^7\) In this method, the film of mold flux solidifies under a little pressure from the cooling block, so air gap can be generated easily between the cooling block and the solidifying film. This state can not be considered as a reproduction of that with pressure from molten steel in the mold.

On account of this point, the estimation in this study is more reasonable than previous studies.

### 4.3. Surface Roughness of the Film

Concerning results of the discussion about \(R_{\text{int}}\) the surface roughness of the film is discussed below.

Using thermal conductivity of air at 500–800 K,\(^15\) the thickness of air gap is derived from \(R_{\text{int}}\) shown in Fig. 13. The calculating result is shown in Fig. 14. The value of \(R_{\text{int}}\) discussed in this study corresponds to about 10 \(\mu\)m of air gap thickness.

In the previous paper\(^7\), average roughness of the outer surface of the film was reported to be about 30 \(\mu\)m. The result shown in Fig. 14 agrees with this thickness of air gap.

Taking the reported values about surface roughness of the film\(^7\),\(^23\),\(^24\) into consideration, the surface roughness varies in the range of 1–150 \(\mu\)m. Surface roughness induced by crystallization of glassy film is about 40 \(\mu\)m, at
most. More roughness is induced by deformation of the film.

Roughness more than 100 μm can be considered to be induced under the condition without static pressure of molten steel, so it is too large as the roughness for the actual state in the mold during casting.

5. Conclusions

Based on the research of mold flux film taken out of the mold after high speed continuous casting, the following results were obtained:

(1) Thickness of the mold flux film is about 1 mm. Not only the crystal phase, but also glassy phase consists the solid layer of the film.

(2) The thickness of liquid layer in the film corresponds to that estimated from mold flux consumption.

(3) In the case that the mold flux film is about 1 mm thick, thermal resistance in the film is equivalent to that on the interface between mold and the film.

(4) As previously reported, values of interfacial thermal resistance are considered to be too large compared with actual state in the mold during the casting. The previous values evaluated under the condition of little static pressure on the interface between mold and the film, but in the actual state with the static pressure, the interfacial thermal resistance should be smaller.

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