Influence of Mold Flux on Initial Solidification of Hypo-Peritectic Steel in a Continuous Casting Mold

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Continuous casting of hypo-peritectic steel was conducted with a pilot slab caster. Such experimental data as local heat flux, thickness of solidified shell or mold flux film, and dendrite primary arm spacing were obtained. On the basis of these experimental results, influence of mold flux on initial solidification in the mold was discussed.

With mild cooling by crystallization of mold flux, local heat flux and solidification rate decreased in the mold. The changes in them quantitatively correspond to each other. Dendrite primary arm spacing increased with the mild cooling. Relationship between the arm spacing and cooling rate was established and cooling rate on quite initial stage of solidification was estimated. Cooling rate at 1 mm thickness of solidified shell was estimated as about 10 000–17 000 K/min and changed by mold flux. Unevenness of the solidified shell thickness becomes remarkable when the shell grows to be 1 mm thick. Relation between the unevenness and the cooling rate was discussed, and critical cooling rate against the uneven solidification was observed around 17 000 K/min. Thermal resistance of mold flux film was also evaluated and it was clarified that thermal resistance in the film is larger than that by air gap, and Crystallization in the film contributes to increase of both resistances. It is also considered that increase of casting speed makes air gap thinner, so reduction of radiation by crystallization of mold flux becomes more important in high speed continuous casting.

KEY WORDS: continuous casting; solidification; mold flux; steel; hypo-peritectic; solidified shell; dendrite primary arm spacing; cooling rate; solidification rate; heat flux; longitudinal surface cracking, film, thermal resistance; unevenness; mild cooling.

1. Introduction

Longitudinal cracking on the surface of a slab is caused by uneven solidification in the continuous casting mold.1,2) In the case that carbon content of steel is 0.10–0.18 mass% for Fe–C binary system, or 0.08–0.16 mass% for practical steel, especially, peritectic reaction induces large shrinkage of solidified shell and the cracking becomes remarkable.3,4)

In order to prevent the uneven solidification and the longitudinal cracking, mild cooling with mold flux is well known to be an effective method. Mold flux infiltrates into the gap between the shell and mold and forms a film there. This film plays a roll of a medium of heat transfer, and it is available for the mean of mild cooling of the shell, increasing thermal resistance by crystallization in it. So designing technologies of mold flux composition have been developed so that crystallization in the film can be promoted, and many results of reducing heat flux in the mold or prevention of the cracking have been reported concerning the actual commercial casting.5–9) On the other hand, many researches on the crystallization in mold flux have also been reported, and it has been turned to be clear that the crystallization brings roughness of the film surface to the mold and reduction of radiation in the film, and they result in increase of thermal resistance of the flux film.10–14)

But it has not been clarified yet, how the solidification phenomena of molten steel changes in the actual continuous casting mold according to the mild cooling of the flux. There have been few reports on this point.5) In order to prevent the cracking, it is surely important to make the solidified shell cooled mildly, while it grows within 1 mm thick and in the distance of several ten millimeters from the meniscus in the mold.15) But there have been few researches on the initial solidification at such an early stage.

In this study, experimental continuous casting of hypo-peritectic steel was conducted with a pilot plant and solidification behavior in the mold was researched. Then, influences of mold flux on the initial solidification of molten steel and heat transfer in the mold were discussed on the basis of those experimental results.

2. Experimental Methods and Conditions

2.1 Continuous Casting

2.1.1 Casting Conditions

Continuous casting of hypo-peritectic steel slab was conducted with pilot plant. Casting conditions are listed in Table 1. 2.5 tons of molten steel was provided and cast into a slab of 100 mm thick and 800 mm wide at casting speed of 1.3–1.5 m/min. Superheat of the molten steel was 80–89 K.
Alloying elements of the molten steel is shown in Table 2. Steel grade was hypo-peritectic with 0.11–0.14 mass% of carbon content. Si, Mn and Al were added and their contents in the steel were the same among each casting.

Three kinds of mold flux were examined in the casting. Their specifications are listed in Table 3. Mold flux A is originally used for low carbon steel and has low basicity (CaO/SiO2) of 0.8 and low solidification temperature. On the other hand, mold flux B and C have higher basicities so that cuspdine, Ca4Si2O7F2: main crystal phase, may adequately crystallize in the film during the casting. Their solidification temperatures were higher and viscosities at 1 570 K were lower according to their higher basicities.

### Section 2.1.2. Local Heat Flux in the Mold

Local heat flux was evaluated in the mold during casting by means of thermo-couples in the mold plate of Cu. Thermo-couples were located in the center in width at 35 mm and 140 mm under the meniscus in the mold, as shown in Fig. 1. Temperature of mold coolant: water was also measured. The actual temperatures during the casting became in stable and constant state for about a minute before the ending, their average values during the last period were employed for the evaluation of the local heat flux.

The local heat flux was evaluated from the result and Eq. (1) as follows;

\[ q = \frac{1}{d_{Cu}} + \frac{1}{\lambda_{Cu}} \left( T_{Cu} - T_{W} \right) \]  

Here, \( q \) indicates local heat flux, \( d_{Cu} \) does distance from mold surface to the position of thermo-couples; 10 mm, \( \lambda_{Cu} \) does thermal conductivity of copper; 377 W/mK, \( h_{W} \) does heat transfer coefficient on the surface to coolant, and \( T_{Cu} \) or \( T_{W} \) does temperature of mold plate of coolant.

\[ h_{W} = \frac{\lambda_{W}}{\sqrt{\frac{Nu}{d_{W}}}} \]  

\[ Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \]  

\[ Re = \frac{d_{W} \cdot V_{W}}{\nu_{W}} \]  

\[ Pr = \frac{C_{Pw} \cdot \eta_{W}}{\mu_{W}} \]  

Here, \( \lambda_{W} \) indicates thermal conductivity of water, \( Nu \) does the Nusselt’s number, \( d_{w} \) does characteristic length; wetted perimeter of slit for coolant, \( Re \) does the Reynolds’ number, \( Pr \) does the Prandtl’s number, \( V_{W} \) does velocity of coolant, \( \nu_{W} \) does kinetic viscosity, \( C_{Pw} \) does specific heat of water, \( \mu_{W} \) does viscosity of water. Physical properties for water were quoted from the literature.

### Section 2.1.3. Thickness of Solidified Shell

Fe–S alloy was added to the molten steel in the mold just before the end of each casting; Fig. 2. The slab was cut after the casting and sulfur distribution on the longitudinal section was transcribed on the printing paper. Thickness of solidified shell was measured on the paper with a vernier micrometer.

### Section 2.1.4. Dendrite Primary Arm Spacing

Specimens were cut out from the surface of slabs. They
were cut out from the center in width. The surface was ground 0.5–8 mm thick and the ground section was etched with picric acid solution. Dendrite structure could be observed like lattice as shown in Fig. 3, and its spacing was measured as dendrite primary arm spacing on the photographs with a vernier micrometer.

2.1.5. Mold Flux Film
Mold flux film was taken out from the meniscus in the mold just after the casting. The film was molded in resin and it whole was cut. The longitudinal section was polished and the structure of the film was observed. It was taken into a photograph and its thickness was measured on it. The section was also analyzed by X-ray diffraction and its intensity at the first peak for cuspidine was evaluated. The device for the analysis was the “X’Pert PRO MPD” by Spectris Co. Ltd.. The target for the X-ray diffraction was Cu and the twice value of diffraction angle, 2θ, was 29.2 deg. for the first peak of cuspidine.

2.2. Experimental Measurement of Apparent Thermal Conductivity of Mold Flux Film

2.2.1. Experimental Apparatus and Evaluating Method
Apparent thermal conductivity was evaluated by fundamental experiment of the parallel-plates method. Apparatus is shown in Fig. 4. W, tungsten plate of 3.5 mm thick was heated by the induction coil placed below, and mold flux was made melted on it at 1723 K. Then, chill block of Cu, whose bottom square of 30 mm side, was settled on the molten flux so that the film might be 2 mm thick. In order to measure temperature, thermo-couples were settled at 4 points; on lower surface of the W plate, in the film at the middle in thickness and two points in the chill block at 5 mm and 10 mm from the bottom surface. On the basis of the measured temperatures, each temperature for the surface or interface of film or chill block was calculated. Thermal resistance of the film was evaluated by Eq. (6)

\[ q = \frac{\lambda_{W}}{d_{W}}(T_{W} - T_{f0}) = \frac{2}{R_{film}}(T_{f0} - T_{f1}) = \frac{2}{R_{film}}(T_{f1} - T_{f2}) \]

\[ = \frac{1}{R_{int}}(T_{f2} - T_{Cu0}) = \frac{2\lambda_{Cu}}{d_{Cu}}(T_{Cu0} - T_{Cu1}) = \frac{2\lambda_{Cu}}{d_{Cu}}(T_{Cu1} - T_{Cu2}) \]

(6)

Here, q indicates heat flux, \( \lambda \) does thermal conductivity, R does thermal resistance and d does thickness. Under script of W, film, Cu and int means W plate, mold flux film, chill block of Cu and the interface between the film and chill block. T indicates temperature and its under script of W, f0, f1, f2, Cu0, Cu1 and Cu2 means the position shown in Fig. 4.

From the seventh term in Eq. (6), substituting each value of thermal conductivity, thickness and temperature, the value of heat flux q was given. Then, the values of \( T_{f0}, T_{f2}, R_{film} \) and \( R_{int} \) were given in order, substituting the values of \( T_{W} \) and \( T_{f1} \).

Finally, apparent thermal conductivity of flux film, \( k_{eff} \) was given by substitution of \( R_{film} \) into Eq. (7).

\[ k_{eff} = \frac{d_{film}}{R_{film}} \]  

(7)

2.2.2. Specifications of Specimens
5 kinds of mold flux were prepared as specimens for the experiment. Their specifications are listed in Table 4. Basicities among them were varied into 0.8, 1.0, 1.3, 1.5 and 1.8.

<table>
<thead>
<tr>
<th>Mold flux</th>
<th>Basicity (−)</th>
<th>Solid. Temp. (K)</th>
<th>Viscosity at 1 573K (Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.8</td>
<td>1 333</td>
<td>0.16</td>
</tr>
<tr>
<td>b</td>
<td>1.0</td>
<td>1 419</td>
<td>0.10</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
<td>1 482</td>
<td>0.06</td>
</tr>
<tr>
<td>d</td>
<td>1.5</td>
<td>1 496</td>
<td>0.06</td>
</tr>
<tr>
<td>e</td>
<td>1.8</td>
<td>1 509</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 4. Specifications of mold fluxes for fundamental experiment.
3. Results

3.1. Continuous Casting

3.1.1. Local Heat Flux in the Mold

Local heat flux at 35 mm under the meniscus in the mold is shown in Fig. 5, as a function of casting speed. Local heat flux was higher for the case of mold flux A, and those for the flux B and C decreased with increase of solidification temperature of them.

3.1.2. Thickness of Solidified Shell

Thickness of solidified shell is shown in Fig. 6 for the case of the flux A, for an instance, as a function of distance from the meniscus in the mold. Solidified shell grew in the process of withdraw, and its thickness was around 1–4 mm and 5–8 mm at 35 mm and at 140 mm below the meniscus, where thermo-couples were located.

Moving time of solidified shell is evaluated by Eq. (8), and it corresponds to solidification time.

\[ t = \frac{l}{V_C} \]

Here, \( t \) indicates solidification time, \( l \) does distance from the meniscus and \( V_C \) does casting speed.

Thickness of solidified shell is shown in Fig. 7 for all the case of mold flux, as a function of square root of solidification time. Thickness of solidified shell was regressed as a function of solidification time in the first period; \( 0 \leq \sqrt{t} < 0.1 \text{ min}^{0.5} \), and as a function of square root of the time in the sec-
ond one; $0.1 \leq \sqrt{t}$ min$^{1/2}$. The results of the regression are also listed in Table 5. Solidification coefficient $k$ differed by the kind of mold flux in the range of $18–25$ mm/min$^{1/2}$. It decreased according to increase of solidification temperature of mold flux.

### 3.1.3. Dendrite Primary Arm Spacing

Dendrite structures beneath the surface of slabs are shown in Fig. 8. Primary arm was observed like lattice in common with all the photographs. The evaluating result of primary arm spacing is shown in Fig. 9 as a function of thickness from the surface. The spacing enlarged with thickness from the surface and differed by the kind of mold flux: the spacing was larger in the case of mold flux A, comparatively.

### 3.1.4. Flux Film

Longitudinal sections of flux film taken out from the meniscus in the mold are shown in Fig. 10. The film for the flux A was glassy and so flexible that it might curve at high temperature when it was taken out of the mold just after the casting. The films for the flux B or C were taken in comparatively flat state but they were partially broken because they were crystalline.

Thickness of the film is shown in Fig. 11 as a function of distance from the meniscus. Each film kept constant thickness in the range of more than 10 mm under the meniscus, and the thickness slightly differed by the kind of mold flux. The average thickness of the film was larger in the case of the flux A glassy; Fig. 12.

### Table 5. A list of solidification constant for each mold flux.

<table>
<thead>
<tr>
<th>Mold flux</th>
<th>$0 \leq t &lt; 0.01$</th>
<th>$0.01 \leq t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$d_{shell} = 101t$</td>
<td>$d_{shell} = 24.8 \sqrt{t} - 1.47$</td>
</tr>
<tr>
<td>B</td>
<td>$d_{shell} = 91.5t$</td>
<td>$d_{shell} = 20.6 \sqrt{t} - 1.14$</td>
</tr>
<tr>
<td>C</td>
<td>$d_{shell} = 87.5t$</td>
<td>$d_{shell} = 18.7 \sqrt{t} - 0.99$</td>
</tr>
</tbody>
</table>

Fig. 8. Dendrite structures beneath the surface of slabs.

Fig. 9. Dendrite primary arm spacing as a function of thickness from surface of a slab.

Fig. 10. Vertical sections of flux film after the casting for each kind of mold flux.

Intensity of X-ray diffraction at the first peak of cuspidine in the flux film is shown in Fig. 13, as a function of solidification temperature. The intensity increased with solidifi-
cation temperature.

3.2. Experimental Measurement of Apparent Thermal Conductivity of Mold Flux Film

Trends of each temperature measured were shown in Fig. 14. It seemed that all of the temperatures became constant at 5 minutes after chill block was settled so that the mold flux might form a film of 2 mm thick. So, thermal resistances were evaluated by the values of temperatures at this moment.

Evaluating result of thermal resistances and apparent thermal conductivity of the film are shown in Fig. 15 as functions of basicity of the flux. Thermal resistance in the film $R_{\text{film}}$ and that on the interface $R_{\text{int}}$ increased with basicity, and apparent thermal conductivity $k_{\text{eff}}$ decreased oppositely. The value of $k_{\text{eff}}$ varied in the range of 2.3–3.0 W/mK by according to the basicity range of 0.8–1.8.

4. Discussions

4.1. Influence of Mold Flux on Solidification Rate and Local Heat Flux

As shown in Fig. 7, solidification rate of solidified shell varied by the kind of mold flux. Here, propriety of the variation is discussed in terms of comparison with change in local heat flux in the mold.

A solidification model can be supposed as shown in Fig. 16, and latent heat by the growth of solidified shell per unit time, $Q'$ can be expressed as Eq. (9).

$$Q' = S \cdot V \cdot \Delta H$$

Here, $S$, $V$ or $\Delta H$ indicates surface area of solidified shell($m^2$), solidification rate($m/s$) or latent heat of fusion ($1.93 \times 10^8$ J/m$^3$), respectively.

Then, latent heat per unit surface area can be given by Eq. (10), as a physical quantity having equal dimensions as heat flux.

$$Q' = \frac{Q'}{S} = V \cdot \Delta H$$

$V$ in Eq. (10) can be obtained by Eq. (11) and $k_i$ listed in Table 5 for each mold flux. Thus, change in $V$ is linearly reflected in $Q'$. 
Figure 17 shows the result of comparison between \( Q' \) calculated by Eq. (9) and experimental values of the local heat flux at the position 35 mm or 140 mm from the meniscus. The both kinds of values agree well each other at each position. Among the values at each position, the tendency can be observed that the both kinds of values decrease by the mild cooling with mold flux, keeping the agreement. This result suggests that the change in growing rate and solidification coefficient by the kind of mold flux is reasonable quantitatively.

4.2. Influence of Mold Flux on Cooling Rate of Solidified Shell

It is generally known that cooling rate of solidified shell can be estimated by measurement of dendrite secondary arm spacing and the Suzuki’s equation\(^{21}\) as follows;

\[
\lambda_{II} R = -710 R^{0.39} \quad (K/min) \quad (C=17.95) \quad (C=5) \quad (K/min) \quad \lambda_{II} = 4700 R^{-0.487} \quad (G>35) \quad (K/min) \quad \lambda_{II} = 310 R^{0.209} \quad (G=5) \quad (K/min)
\]

Here, \( G \) can be calculated from local heat flux \( q \) and thermal conductivity of the solidified shell \( \lambda \), by Eq. (14).

\[
G = \frac{q}{\lambda}
\]

On the other hand, dendrite primary arm spacing \( \lambda_{I} \) can be read in Fig. 8, for the corresponding thickness of solidified shell to the position of thermo-couples in the mold. The obtained relation between \( \lambda_{I} \) and \( R \) is shown in Fig. 18. The previous data\(^{22}\) obtained in the high speed continuous casting were added to those in this study. \( \lambda_{I} \) decreased with increase of \( R \). The relation between them was regressed as Eq. (15).

\[
\lambda_{I} = 4700 R^{-0.487} \quad \lambda_{I} = 310 R^{0.209} \quad \lambda_{II} = 710 R^{0.39} \quad \lambda_{II} = 4700 R^{-0.487}
\]

T. Edvardsson \textit{et al.} previously reported that relationship obtained experimentally in the condition of smaller cooling rate. The result in this study generally agrees with it but the tendency of the spacing on cooling rate in this study is a little larger than that by T. Edvardsson. The reason for this difference seems that the dendrite structure grew under the condition of wider range of \( G \) in this study.

Cooling rate was derived from the primary arm spacing through Eq. (15). The result is shown in Fig. 19 as a function of thickness from the surface of a slab. It is observed that cooling rate decreases with growth of the solidified shell and the cooling rate for mold flux A is a little larger than the others in the range within 5 mm of the thickness.

Cooling rate derived from the primary arm spacing in this way is compared with what is calculated by Eq. (12) at 35 mm below the meniscus. Cooling rate by the spacing was evaluated as average values in the range of 2–3 mm for

\[
V = \frac{\partial d_{shell}}{\partial t} = \frac{k}{2\sqrt{t}} \quad (11)
\]

Figure 17 shows the result of comparison between \( Q' \) calculated by Eq. (9) and experimental values of the local heat flux at the position 35 mm or 140 mm from the meniscus. The both kinds of values agree well each other at each position. Among the values at each position, the tendency can be observed that the both kinds of values decrease by the mild cooling with mold flux, keeping the agreement. This result suggests that the change in growing rate and solidification coefficient by the kind of mold flux is reasonable quantitatively.

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solidified shell thickness, corresponding the position below the meniscus. The result of this comparison is shown in Fig. 20. Both cooling rate agrees well each other, and decreases with crystallization of mold flux.

It is summarized that dendrite primary arm spacing varied corresponding to cooling rate, and evaluation of cooling rate is possible at so early a stage of solidification that secondary arm spacing is too difficult to be measured for the evaluation of cooling rate. Change in cooling rate by mold flux can be evaluated from the primary arm spacing.

4.3. Influence of Mold Flux on Evenness of Solidified Shell Thickness

It was discussed quantitatively in the aforementioned paragraphs that the local heat flux, solidification of the shell and the dendrite arm spacing, those are induces by crystallization of mold flux, change corresponding to each other. In this paragraph, the other change by crystallization of mold flux is discussed in terms of evenness of solidified shell thickness.

As an index of evenness, standard deviation of solidified thickness shown in Fig. 7, standard deviation was evaluated and is shown in Fig. 21. The standard deviations increase with growth of solidified shell, and that for mold flux A, which has the largest cooling rate, is larger than those for the other flux. The difference in standard deviation by mold flux begins to generate at the point on which solidified shell grows to be about 1 mm thickness. This point corresponds to the period of 0.1–1 s for solidification time, which was also reported previously as the initiating period uneven solidification.24) About 1 mm of the standard deviation at 1 mm thickness is seemed to be criteria for uneven solidification of the shell.

Here, ratio of the standard deviation to the thickness is evaluated and defined as an index of unevenness for the solidified shell. This index at more than 1 mm thickness of the shell is shown in Fig. 22 as a function of distance from the meniscus. The index decreases with growth of the shell. The index for mold flux A is larger than those for others especially in the range of 20–40 mm from the meniscus.

The maximum value of the index is shown in Fig. 23 as a function of cooling rate when solidified shell is 1 mm thick.
this figure that the maximum value of the index rapidly increases when cooling exceeds $1.7 \times 10^4$ K/min. This result suggests the existence of the critical cooling rate against the occasion of uneven solidification, in spite that some room remains for more quantitative discussion.

The results in this paragraph leads a suggestion that mild cooling is important for the shell to make even growth on such early stage of solidification that its thickness becomes within 1 mm, and effect of mild cooling by crystallization of mold flux acts on just this stage so as to prevent depression or longitudinal cracking of solidified shell.

4.4. Effect of Crystallization of Mold Flux on Thermal Transfer in the Mold

It is well known that the mild cooling is brought by crystallization of mold flux film in the mold, by means of increase of thermal resistance on the surface to the mold or reduction of radiation. However, thermal resistances concerning with the flux film have not evaluated before in the actual continuous casting. So it has not been clarified yet how the crystallization makes thermal resistance of the film increased. In this paragraph, thermal resistance of the film is estimated on the basis of the results of continuous casting and basic experiment, and mild cooling effect by crystallization of mold flux is discussed in terms of the resistance.

Thermal transfer from the solidifying interface to the thermo-couples in the mold can be expressed as Eq. (16) and shown in Fig. 24, schematically.

$$ q = \frac{\lambda_{\text{air}}}{d_{\text{air}}} (T_0 - T_1) = \frac{k_{\text{eff}}}{d_{\text{film}}} (T_1 - T_2) $$  

$$ = \frac{\lambda_{\text{air}}}{d_{\text{air}}} (T_2 - T_3) = \frac{\lambda_{\text{Cu}}}{d_{\text{Cu}}} (T_3 - T_4) $$  

(16)

Here, $T$ or $\lambda$ indicates temperature or thermal conductivity, and subscript of 0, 1, 2, 3 or 4 does the positions of solidifying interface, surface of the mold to the film, surface of the film to the mold, and surface of the mold or thermo-couples in the mold.

Supposing $T_0$ to liquidus of the steel, $T_1$ and $T_2$ are calculated in order. Then supposing $d_{\text{air}}$ so that calculated value of $T_4$ may agree with that of experimental, all of the unknown values including $T_3$ are obtained. Here, it is supposed that curvature of the surface of the film can be ignored and the air gap has uniform thickness.

Results of calculation for each thermal resistance at 35 mm below the meniscus are shown in Fig. 25. Thermal resistance $R_{\text{film}}$ is larger in comparison with interfacial resistance $R_{\text{int}}$. In comparison among the mold flux, both resistance of $R_{\text{film}}$ and $R_{\text{int}}$ increase with solidification temperature of mold flux, and the mold flux C has the largest resistances. Comparing mold flux A with those of B and C, $R_{\text{film}}$ seems to make little difference in spite of large difference in solidification temperature. The reason can be considered to be that decrease of apparent thermal conductivity $k_{\text{eff}}$ for the mold flux B and C was cancelled out by that of the film thickness. Difference in $R_{\text{film}}$ between the mold flux B and C can be explained by that in their thickness.

Cooling rate at 1 mm of the shell thickness is shown in Fig. 26 as a function of total value of $R_{\text{film}}$ and $R_{\text{int}}$. It is observed that an obvious relationship exist between them, and it can be concluded that increase of thermal resistance by crystallization of the film makes cooling rate decreased.
5. Conclusions

Continuous casting of hypo-peritectic steel was conducted with pilot slab caster, and influence of mold flux on the initial solidification in the mold was investigated, and some results were obtained.

1. Solidification rate of the shell changes according to mold flux. Applying the crystalline flux, local heat flux decreases and solidification rate of the shell decreases accordingly. The change in solidification rate quantitatively corresponds to that in local heat flux.

2. Dendrite structure in the solidified shell changes according to mold flux. Applying the crystalline flux, primary arm spacing increases.

3. By means of measurement of the primary arm spacing, cooling rate can be estimated on such an early stage of solidification that the shell grows within several mm thick.

4. Unevenness of solidification becomes apparent when the solidified shell grows 1 mm thick. Prevention of uneven solidification is brought by mild cooling with mold flux on quite an early stage.

5. In the range of 35–45 mm below the meniscus, thermal resistance in flux film is larger than that by air gap.

6. Crystallization in the mold flux film contributes to reduction of radiation and increase of thermal resistance by air gap.

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