Development of Mold flux for Continuous Casting of Type-304 Stainless Steel

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Synopsis

Casting experiments using high viscous mold flux were performed in order to eliminate defects from the surface of a type-304 stainless steel slab.

Despite the fact that high viscous mold flux reduced the depth and the degree of the surface segregation of the oscillation marks, we observed dispersion defects transverse to the direction of casting on the slab surface.

In this paper, we have considered a hypothesis regarding the mechanism of depression fromation related to heat transfer from the initial solidefied shell and the mold surface through the mold flux film, as well as depression formations related to the flow of mold flux into the space between the solidified shell and the mold.

The experiments showed a non-uniform mold flux flow into the gap between the solidified shell and the mold, and, as a result, the excess amount of mold flux flow caused the depression.

A mold flux designed with a thermo-fluid consideration of the physical properties (i.e., decreasing the thermal conductivity of the mold flux) and taking into account the viscosity could prevent the formation of surface depressions and reduce the oscillation mark depth and surface segregation.

1. Introduction

Since the scale-off in the hot rolling of stainless steel can be as little as a few hundredths of μm, the surface properties of the casting slabs have a significant effect on the surface properties of the final product. This is evident in the variations in luster caused by the segregation zone in the slab surface[1], thus making it difficult to guarantee a flawless product.

Therefore, the surface quality of the slab must be improved.

With this in mind, the authors performed experiments using high viscosity mold fluxes in order to reduce not only the depth of the oscillation marks (OSM) that result from the use of forced cooling for the initial solidified shell of Type-304 stainless steel slabs, but also the depth of the segregation zone.

This paper will explain the results of these experiments, in which high viscosity mold fluxes were used, and then analyze, with a focus on the behavior of the mold flux flow, the mechanism that generates the depressions, which is normally a drawback when using high-viscosity mold fluxes.

2. Concept of Forced Cooling in the Mold

The concept for reducing the depths of the OSM and the segregation zone is illustrated in Fig. 1. The solidified shell is forcibly cooled to improve the strength of the steel. This way the deformation in the shell caused by the mold flux flow is minimized and the OSM depth is reduced. The strength and the ductility of the steel are also improved to minimize any outflow of internally concentrated molten steel due to breakage of the shell. As a result, the depth of the segregation zone is reduced[2]

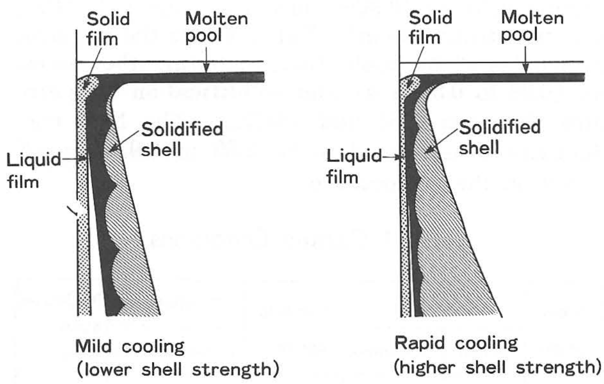


Fig.1 Concept for Reduction of Oscillation Mark Depth and Segregation Zone

The heat transfer in the meniscus located inside the mold depends on the thermal characteristics that exist between the coolant water and copper plate, as well as between the injected copper plate, the galvanized layer, and the mold flux film. If we set the value of the heat resistance between the coolant water and the copper plate as one, then that of the copper plate is 3, the mold flux solidified layer is 4, and the mold flux film is 10. As a result the highest heat resistance inside the mold is that of the mold flux film, and the mold flux film together with the solidified layer accounts for 80% of the total heat resistance. To ensure forced cooling inside the mold, it is necessary to increase the heat conductivity of the mold flux itself, otherwise, the thickness of the mold flux film will have to be reduced.

However, it is difficult to change the heat conductivity significantly within the composition limitations of the existing slag mold fluxes[3]. It would be more effective to the reduce the thickness of the mold flux film.

3. Experiments and Analyses

3.1 Casting Conditions

When it comes to casting steel, the general belief is that the mold flux film can be reduced by high mold flux viscosity[4], high velocity[4], and high cycle[5], and short stroke[6] oscillation. Keeping these effects in mind, we conducted casting tests using different viscosity mold fluxes under fixed casting conditions for slabs in No. 1 CCM at the Hikari Steel Works. Table 1 shows the casting conditions, including the slab size (1245 mm×143mm), the grade of steel (Type-304), the casting velocity (0.90m/min.), the cycle (2.5Hz), and the stroke (6mm). Table 2 lists the physical properties of the mold flux, including the viscosity (0.08 to 0.30Pa·s) and solidification temperature (between 1383 and 1443K). The heat conductivity is estimated to be 0.80 to 0.93W/m·K based on the composition.

Table 1 Casting Conditions

Steel grade	Slab size		Casting speed	Oscillation		Negative strip time
	Width	Thickness		Cycle	Stroke	
SUS304	1245mm	143mm	0.90m/min	2.5Hz	6mm	0.159sec

Table 2 Physical Properties of Mold flux

Viscosity at 1573K Pa·s	Solidification temperature K	Thermal conductivity W/mK
0.08 ~ 0.30	1383 ~ 1443	0.80 ~ 0.93

$$\lambda = 1.26 - 0.3 \cdot \frac{X_{CaO} + X_{MgO} + X_{Na_2O}}{X_{SiO_2} + X_{Al_2O_3}} \quad (W/mK)$$ [1)]

3.2 Analyses on Casting Slabs

A profile meter was used to measure the OSM depth over a length of 300mm in the direction of casting at 50 to 100mm pitches for the full width of slab. The depth of the segregation zone was measured from test pieces taken from longitudinal sections of the slab.
In order to identify the effect of the mold flux properties on the thermal characteristics inside the mold, the solidification cooling rate was estimated from the secondary dendrite arm spacing in the surface layer of the slab[7]. Using a combination of the solidification cooling rate and one-dimensional heat transfer analysis, the heat transfer coefficient in the vicinity of the meniscus was calculated with an actual product. When casting was performed with high viscosity mold fluxes, depressions normal to the casting direction were formed due to an excess of mold flux flow toward the interior. The heat transfer coefficient in the depression was also calculated, and the thickness of an excess mold flux flow toward the interior was estimated based on the calculated heat transfer coefficient.

4. Experimental Results

4.1 Surface Properties

Fig. 2 illustrates the effect of mold flux viscosity on the mold flux consumption and solidification cooling rate at a depth of 200μm from the surface layer and the OSM depth. The higher the mold flux viscosity, the greater the reduction in mold flux consumption is reduced. This is about 60% for 0.20Pa·s and higher mold fluxes, as opposed to the 0.08Pa·s mold flux.

Moreover, the higher the mold flux viscosity, the higher the cooling rate.
The higher the mold flux viscosity, the greater

the reduction in the depths of OSM and the segregation zone. This improvement is particularly noticeable when the mold flux is 0.20 Pa·s. This is because the higher viscosity mold fluxes have thinner thicknesses and lower heat-resistance values.

Based on these data, the authors attributed the reduction in the depths of OSM and the segregation zone that resulted from the use of high viscosity mold fluxes to improved strength and ductility of the initial solidified shell brought about by forced cooling.

With viscosity mold fluxes of 0.20Pa·s and higher, however, the occurrence of depressions transverse to the casting direction is dependent on the properties of the mold fluxes, even when the same viscosity mold fluxes are used.

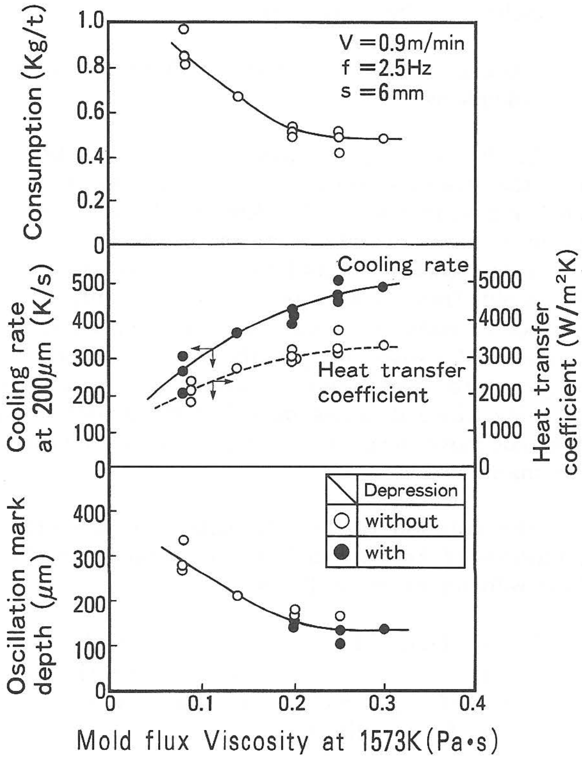
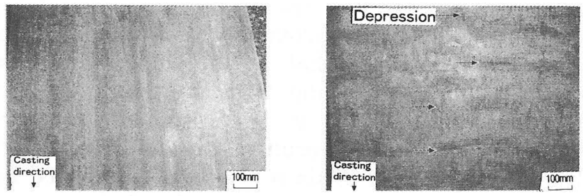


Fig. 2 Effect of Mold Flux Viscosity on Mold Flux Consumption, Cooling Rate and OSM Depth



(a)0.25Pa•s (lower thermal conductivity)

(b)0.25Pa•s (higter thermal conductivity)

Fig. 3 Appearance of Type SUS 304 Slabs Cast with High-Viscosity Mold Fluxes

4.2 Performance of Depression

Fig. 3 is a photograph of the slab on which 0.25Pa·s mold fluxes were used. The depressions came in 200mm pitches (which corresponds to a casting time of 13 s and a 32-cycle mold oscillation) in the same direction as the OSM. The depth of the depression were 2 to 3mm, and the length in the casting direction was approximately 50mm (which corresponds to a casting time of 3 s and an 8 cycle mold oscillation); the width extended to the full width of the slab in some parts.

Fig. 4 shows the transition of the solidification cooling rate in the direction of casting in relation to the depth and location of the depression (10,100,200 μm from the surface layer)[8]. The cooling rate at a depth of 10 μm from the surface layer is 1600K/s, while the rate at the depression is 70K/s.

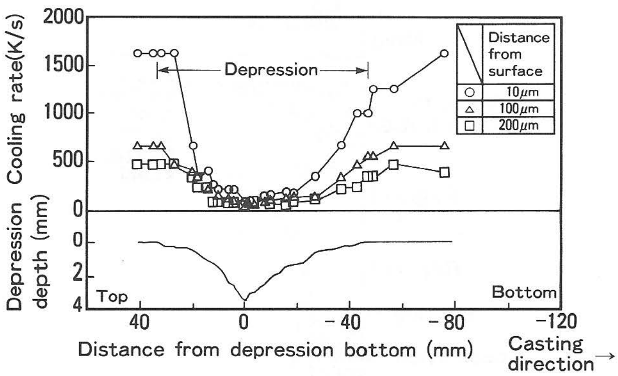


Fig. 4 Transition of Depression Depth and Casting Rate in Casting Direction

A delay noticed in the solidification from the topmost surface layer was presumably caused by excess mold flux inflow. By calculating the heat transfer coefficient based on the solidification cooling rate, the thickness of the mold flux film was found to be approximately 0.1mm in the normal areas, while that at the depression was about 1mm. Considering that the depth of this depression was 3mm, it is presumed that the depth increased as a result of the deformation of the solidified shell. This is due to a difference in the thermal contraction as a result of the transformation δ / γ.

5. Discussions

5.1 Behavior of Mold Flux Flow

The behavior of the mold flux flow, and the part that the mold flux properties played in the generation of the depression are herein discussed.

The temperature distribution throughout the mold flux molten layer and the mold flux film was between 1373K (the mold flux solidification temperature) and 1773K (the molten steel temperature). Therefore, the viscosity of the inflow mold flux is estimated to be from 0.01 to 1 Pa·s. Moreover, as illustrated schematically in Fig. 5, the distance between the mold surface and the molten steel or slab surface changes continuously between 10 to 0.1mm. Such a continuous change is attributable to the behavior of the mold flux flow.

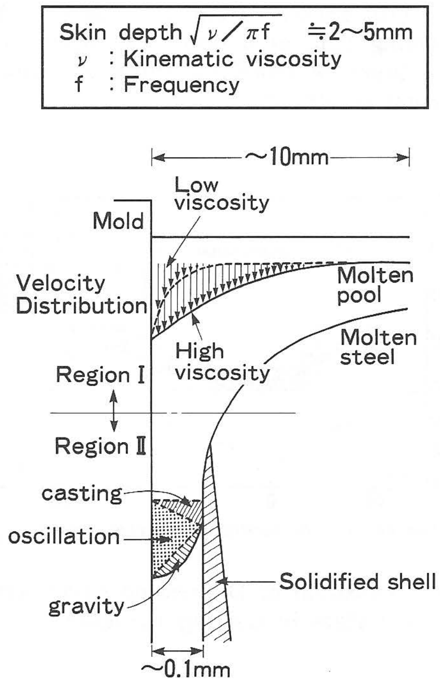


Fig. 5 Schematic View of Mold Flux Flow in the Continuous Casting Mold

The mold flux velocity distribution is calculated in Eq. 1

$$\theta U/\theta t = \theta(\nu\, \theta U/\theta x)/\theta x + g \cdots\cdots \text{Eq. 1}$$

where,
U = mold flux flow velocity
x = the distance from the mold surface in the direction of the mold flux flow
ν = dynamic viscosity (viscosity/density) and
g = acceleration of free fall.

In this case, the value that refers to the length in which the mold oscillation of cycle f has an effect on the behavior of the mold flux flow with kinetic viscosity ν, (i.e., the skin depth $\sqrt{\nu/\pi f}$), is 2 to 5mm under normal casting conditions. It is necessary to consider the behavior of the mold flux flow by creating two regions with regard to the skin depth: in the vicinity of the meniscus (Region I) and the portion between the mold and the slab (Region II).

(1) Region I (Behavior in the Vicinity of the Meniscus)

In this region, the mold flux molten layer, and the distance between the mold and molten steel are larger than the skin depth, and correspond to the side where the mold flux flows in. For purposes of simplification, the behavior of the mold flux flow was considered only with respect to mold oscillation, and not with respect to free fall caused by gravity or with respect to temperature distribution brought on by kinetic viscosity, since it is assumed that the molten steel does not move because it is supplied in a continuous manner.

The solution of Eq. 1, using the boundary conditions of Eqs. 2 and 3, result in the mold flux flow velocity given in Eq. 4.

$$U = \pi s \cdot f \cdot \cos(2\pi f \cdot t) \quad \text{at } x=0 \cdots\cdots \text{Eq. 2}$$
$$U = 0 \quad \text{at } x=\infty \cdots\cdots \text{Eq. 3}$$
$$U = \pi s \cdot f \cdot \exp(-x\sqrt{\pi f/\nu}) \cdot \cos(x\sqrt{\pi f/\nu} - 2\pi f \cdot t) \cdots\cdots \text{Eq. 4}$$

where,
f = cycle of mold oscillation, and
s = stroke of mold oscillation.

Based on Eq. 4, in this Region, the further the mold flux flow moves away from the mold, the greater the exponential reduction in the mold flux flow velocity. On the other hand, the oscillation becomes more effective the higher viscosity becomes, even where it is remote.

Therefore, the higher the mold flux viscosity, the higher the mold flux inflow even when the mold oscillation remains the same. In addition, by taking the temperature inside the mold flux and its flow velocity distribution into account, the mold flux viscosity near the mold-namely, the viscosity around the temperature of mold flux solidification, is essential.

(2) Region II (Behavior between Mold and Slab)

In this Region, the distance between the mold and slab is smaller than the skin depth, and corresponds to the side where the mold flux flows out. The solution of Eq. 1 under the conditions of Eqs. 5, 6 and 7 results in Eq. 8 for the mold flux flow velocity. It is a linear approximation.

$U=\pi s \cdot f \cdot \cos(2\pi f \cdot t)$ at $x=0$······Eq. 5
$U=V$ at $x=d$······Eq. 6
$U=《\sqrt{\nu / \pi f}$······Eq. 7

$U=\pi s \cdot f \cdot \cos(2\pi t \cdot t) \cdot (d-x)/d + V \cdot x/d + g \cdot x \cdot (d-x)/2\nu$ ······Eq. 8

where,
d=distance between mold and slab.

Eq. 8 shows that in this region the mold flux flow velocity changes linearly between the mold and the slab due to oscillation of the mold and pull-off of the slab, without demonstrating any effect on viscosity.

Because of gravity, the flow velocity decreases as the viscosity increases until it reaches a peak at the mid-point between the mold and the slab. Taking the account the fact that the distance between the mold and the slab is small, the temperature distribution throughout the mold flux film is linear, and the temperature at the mid-point is the mean temperature between 1373 K and 1773, or approximately 1573 K.

Therefore, in this Region, the higher the mold flux viscosity, the greater the mold flux outflow; In other words, its consumption is reduced. The mold flux viscosity is applicable to the value corresponding to 1573 K.

Fig. 6 indicates the relationship bewteen the mold flux viscosity and the mold flux flow rate. In this figure, the calculated maximum film thickness is at the time when the mold lowering velocity is maximum; in other words, where the thickness at which the inflow rate, determined by the integration of Eq. 4 and the length, is equivalent to the outflow rate determined by the integration of Eq. 8 with the distance of Eq. 8 and the length.

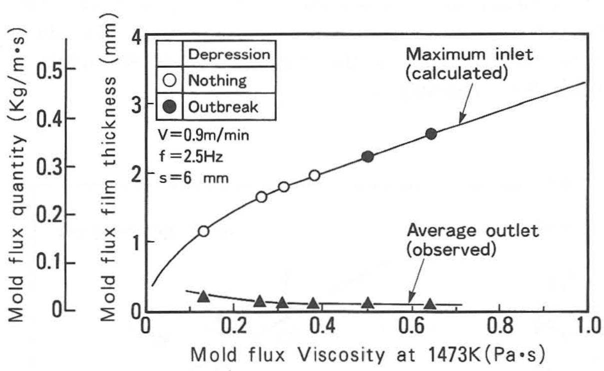


Fig. 6 Relationship between Mold Flux Viscosity and Powder Flow Rate

Moreover, the outflow rate is obtained by calculating the mold flux consumption, density and casting velocity used in the casting tests on an actual product. The calculated value is the time mean value.

Since the mold flux viscosity that will be applied needs to approximate that of the mold, the viscosity shown in the figure is 1473 K.

In the vicinity of the meniscus, the higher the mold flux viscosity, the higher the inflow rate obtained through oscillation of the mold. However the outflow rate between the mold and the slab because of gravity, tends to decrease further. Because of the imbalance between the inflow and the outflow, the flow tends to become more uneven as the mold flux viscosity increases.

In order to prevent depressions, we must take into account the dependence of mold flux viscosity on the temperature, and on the viscosity distribution in the vicinity of the meniscus.

5.2 Relationship between Mold Flux Properties and Depressions

In order to prevent depressions, we must take into account the dependence of the mold flux viscosity on the temperature and on the viscosity distribution in the vicinity of the meniscus. Therefore, we studied the relationship between these mold flux properties and depressions using heat conductivity and medium carbon steel[9] as characteristic values of the dependence of mold flux viscosity on the temperature (α).

Fig. 7 indicates the relationship of the mold flux viscosity at 1573 K and α to the occurrence of depression. As shown in the figure, the depression can be prevented by lowering the thermal conductivity of the mold film in accordance with the viscosity[10].

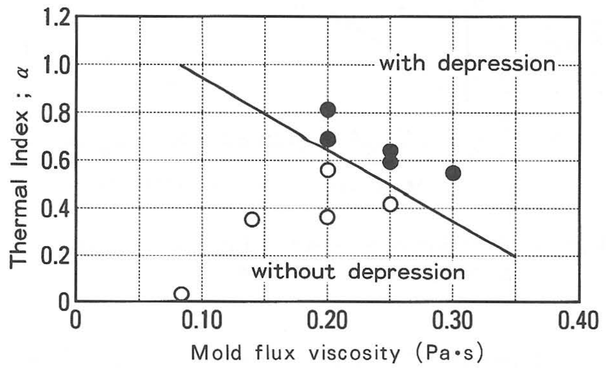


Fig. 7 Relationship between Mold Flux Properties and Depression on Type SUS 304 Slabs

Oxides that can reduce thermal conductivity α are those that can also reduce the dependence of mold flux viscosity on the temperature[11]. Therefore, by lowering α in accordance with the viscosity at 1573 K we can minimize the increase in viscosity in the mold flux and also equalize the imbalance between the inflow and the outflow. This way, the depression can be prevented.

6. Summary

In order to reduce the depths of the oscillation marks and segregation zone that occur with forced cooling of the initial solidified shell, experiments were conducted with mold fluxes of various viscosities. The behavior of the mold flux flow and heat conductivity were then analyzed, and the following conclusions were drawn.

(1) High viscosity mold fluxes are effective in forced cooling for the initial solidified shell since they reduce the depths of oscillation marks and segregation zone.
(2) The higher the mold flux viscosity, the greater the depression is in a direction nomal to the casting direction in some parts. This is due to excessive unevenness in the mold flux inflow.
(3) Depressions can be prevented by optimizing the heat conductivity of the mold flux viscosity at 1573 K. This is attributable to the equalization of the inflow and outflow of the mold flux by minimizing the viscosity increase in the mold flux.

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