Perspectives of Research on High-speed Conventional Slab Continuous Casting of Carbon Steels

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Two decades ago the casting speed of the conventional slab continuous caster was increased stepwise to a level over 2 m/min. Henceforth, the casting speed has been remained a similar level. In this review the reasons for constraining the casting speed are discussed. As a result the constraints of the high-speed casting are thought mold powder entrapment and longitudinal facial crack occurring in high-speed casting.

Some measures to prevent the mold powder entrapment and the longitudinal facial crack are discussed. Resultantly the research issues we should develop are considered such as prevention of alumina built-up in a submerged entry nozzle, control of fluid flow in a mold and control of heat transfer through mold powder film intervened between a solidifying shell and a mold wall. They are most important to realize the high-speed continuous casting of conventional slab.

KEY WORDS: high-speed casting; conventional slab; mold powder entrapment; longitudinal facial crack; upper limit of casting speed.

1. Introduction

Many continuous casters have been built and operated in Japan since the first slab continuous caster was built in Hikari Works¹⁾ in 1960. The production ratio of carbon steel slab produced by the continuous casters to the total production of slab reaches 99.6% in 1999.²⁾

When a continuous caster began to be operated, the production capacity of one continuous caster was less than 100 thousand tons per month.³⁾ In the 1970s, the casting operation began to be more stable, both the casting speed and the production amount were increased because the reliability of the caster was improved and the accidents on casting operation was reduced. In 1973, a high-speed casting of 2 m/min was succeeded in Fukuyama No. 2 slab caster of NKK.⁴⁾ At those time many engineers worked in a continuous casting process had great interest in high-speed casting technology, which was one of technological issues.

The transition of casting process is shown in Fig. 1.⁵⁾ The casting process had been changed from ingot making process to continuous casting process with a slab thickness of 200 to 280 mm (conventional slab casters) since the 1960s. In the future, the conventional slab caster might be replaced by a thin slab caster with a thickness of less than 100 mm.⁶⁾ A twin roll strip caster⁷⁾ with a thickness of 1 to 5 mm also started to be industrialized several years ago. Like this, although the casting process is directed toward a thin slab caster or a strip caster in the future, at present almost all the production of steel slab is cast with the conventional slab casters. Accordingly, the casting technologies of the conventional slab casters should be improved further when the thin slab caster begins to be a main caster instead of the conventional slab caster.

The practices and the principles underlying continuous casting technologies were summarized in a reference text entitled “History of Development of Continuous Casting Technologies in Japan”¹⁾ edited by ISIJ. A review paper collection entitled “Latest Development of Continuous Casting Technologies”⁸⁾ was also published by JSPS (Japan Society of Promotion of Science).

The purpose of the present work is to clarify troubles or problems occurring in high-speed casting of carbon steel slab with the conventional slab caster and discuss some research issues.

2. Needs of High-speed Casting Technology

The production rate (ton/month) of the slab caster is shown in Fig. 2⁹⁾ vs. the slab thickness with a parameter of casting speed. The production rate of a hot strip mill attains about 400 thousand tons per month. Comparing the production rate of the slab caster with that of the hot strip mill, even the production rate of the conventional slab caster does not attain that of the hot strip mill. The production rates of the thin slab caster and the strip caster are smaller than that of the conventional slab caster. Hence, several casters are necessarily built in order to meet the production rate of casters to that of the hot strip mill. Consequently, if the productivity of the slab caster could be increased, the number of slab casters can be reduced, and also labor-cost and energy can be saved. One example of ideal processes seems to be that one caster is connected to one hot strip mill. For a conventional slab caster with one strand, the casting speed should be increased over twice the present casting speed, approximately 4 m/min. This speed is thought one of targets in the near future. Furthermore, in

 Fig. 1. Transition of casting processes.⁵⁾

 Fig. 2. Relationship between the productivity of continuous slab caster and the slab thickness as a parameter of casting speed.⁹⁾

order to realize the ideal process, *i.e.*, full hot direct rolling, technologies for more stability of the casting practice and the production of higher slab quality should be realized.

The casting speed of the conventional slab caster with an oscillating mold has been remained a 2 m/min level because such higher-speed casting deteriorates slab quality. Therefore, we will investigate what the factors for restraining the casting speed of the conventional slab caster are.

3. Present State of High-speed Continuous Casting of Steel Slab

3.1. Trend of Casting Speed of Conventional Slab Continuous Caster

We will survey the present state of high-speed casting in a conventional slab caster. The trend of the casting speed is shown in Fig. 3¹⁰⁾ for the conventional slab casters in Japanese steel companies. The main specifications and the casting speed are listed in Table 1 of the conventional slab

casters.¹¹⁻¹⁸⁾ The casting speed has been stepwise increased and attained approximately twice in two decades. Fifteen years ago a synchronized operation began between a continuous caster and a hot strip mill, *i.e.*, hot direct rolling.¹⁹⁾ Since the hot direct rolling operation needs the productivity of the caster to be met to that of the hot strip mill, the casting speed should be increased.

3.2. Heat Transfer and Lubrication Phenomena in Continuous Casting Mold at High-speed Casting

The infiltration of liquid powder into a shell/mold gap is a very important process in continuous casting since it is necessary to ensure both good lubrication and uniform heat transfer between a shell and a mold. Failure to provide these conditions could result in the creation of surface defects and sticker breakouts.

We will survey the heat transfer and the lubrication phenomena in a mold at a casting speed over 2 m/min of slab casters.

Local heat flux in casting of low carbon Al killed steel is shown in Fig. 4²⁰⁾ against the remaining time in a mold. The local heat flux during the conventional slab casting given by Suzuki *et al.*,²¹⁾ and Grilles,²²⁾ and a medium thickness slab casting by Watanabe, *et al.*, are plotted in this figure. Comparing the local heat fluxes by Suzuki *et al.* and Watanabe *et al.* with that by Grilles, a large difference appears within about 10 sec. After about 10 sec the local heat flux is comparatively in good agreement with one another. The difference in the initial 10 sec is supposed to occur caused by mold powder characteristics. When a shell is thinner, the heat flux is greatly influenced by thermal resistance of mold powder film. On the other hands, when the shell is thicker in a lower part of the mold, since the thermal resistance of a shell begins to be large with shell thickness, the shell is supposed to control the heat transfer.

A poor lubrication frequently causes a breakout because a shell is stuck to a mold wall and ruptured, and subsequently molten steel is flown out of the ruptured point. Such this breakout does heavy damage to the caster.

One of the functions of mold powder is lubrication between a shell and a mold wall. A consumption rate of mold powder is one of the judgement factors of a stable casting

Table 1. Main specifications of conventional slab casters with high productivity of Japanese steel companies.

Company	Nippon Steel			NKK		Kawasaki	Sumitomo	Kobe
	Ohita No.4	Nagoya No.2	Kimitsu No.3	Fukuyama No.5	Fukuyama No.6	Mizushima No.5	Kashima No.3	Kakogawa No.4-2
Type	V-B	V-B	V-B	V-B	V-B	V-B	V-B	V-B
Tundish (t)	70	60	60	80	80	70	65	80
Number of strands	2	2	2	2	1	2	2	1
Mold length (mm)	950	900	900	950	950	900	900	900
Slab size (mm)	Thickness	280	245	240	220	220-300	220	220
	width	1950	1300	1500	700-1650	675-2100	850-1900	700-1600
Machine length (m)	44.5	48.4	43.0	42.1	49	45	42.7	40.5
Casting speed (m/min)	LC, ULC	1.5	2.0	1.8	2.5	2.5	2.3	2.0
	MC	1.5	—	—	1.8	2.0	1.8	2.0
	(max.)	(1.6)	(2.5)	—	(3.0)	(3.0)	(2.5)	—
Ref.	(13,17)	(17)	(18)	(11)	(12)	(16)	(15)	(14)

V-B: vertical bending type, LC,ULC,MC: low carbon Al killed steel, ultra low carbon Al killed steel and middle carbon steel, respectively

Fig. 3. Transition of casting speed of main slab casters in Japanese steel companies.¹⁰⁾

Fig. 4. Relationship between the local heat flux and the remaining time in a mold of solidifying shell of low carbon Al killed steel.²⁰⁾

or not. A high consumption rate of mold powder improves lubrication in a mold. **Figure 5**²⁶⁾ shows the relationship between the mold powder consumption rate and the casting speed as a parameter of a mold oscillation curve. The consumption rate, Q_p , per unit interfacial area between a shell and a mold wall is decreased with casting speed. Thus, many researchers^{23,24)} studied infiltration phenomena and derived empirical equations for estimating the mold powder

Fig. 5. Influence of casting speed on the mold powder consumption rate.²⁶⁾

consumption rate. Itoyama and Bessho²⁵⁾ summarized the regressed equations for estimating the consumption rate of mold powder published in the last twenty years. Some of these regressed equations are given in **Table 2**. The regressed equations reported in the 1980s are comparatively simple formulas. However, the latest regressed equation is a complicated formula expressed as a function of casting speed, mold oscillation conditions, and characteristics of mold powder such as viscosity and crystallization temperature. Since all equations are regressed ones determined empirically, they are valid within the experimental conditions. However, they might be not valid when the casting conditions are out of the experimental ranges. Hence, we should theoretically analyze the infiltration phenomena of the mold powder and derive a new estimation equation.

The overall mold powder consumption is mainly expressed in kg/ton of steel or in kg/m² of strand. The mold powder consumption is regarded to be a measure of the average quantity of mold powder infiltrated into a shell/mold gap. The consumption rate of mold powder 0.3 kg/m² has been taken as a criterion for the judgement of good or poor lubrication.²⁶⁾ However, in a thin slab caster, the consumption rate was reported less than 0.1 kg/m² at a casting speed of 5 m/min.²⁷⁾ Accordingly, we should reconstruct a more accurate critical consumption rate of mold powder, or search for a different factor expressing casting stability instead of the powder consumption rate.

Table 2. Various regressed equations for estimating the consumption rate of mold powder published previously.

Year	Researcher	Regressed equation
1980	M. M. Wolf	$Q_p = 0.7(\eta \cdot V_c^2)^{-0.5}$
1980	K. Kawakami et al.	$q_p = k \cdot t_p, \quad Q_p = q_p \cdot f / V_c$
1984	M. M. Wolf	$Q_p = 0.55(60/f)(\eta V_c^2)^{-0.5} + 0.1$
1987	K. Koyama et al.	$Q_p = 0.6(\eta V_c)^{-1}$
1988	Y. Nagano et al.	$Q_p = 0.33/V_c^{0.29} + 0.052/(\eta \cdot V_c^{1.86})$
1989	Y. Imada et al.	$q_p = (-3.15 \log \eta_s + 5.117)p$
1991	O.D.Kwon et al.	$Q_p = 0.40(2/S^{0.3})(60/f)(\eta V_c^2)^{-0.5} + 0.22$
1993	M.M.Wolf	$Q_p = 0.5(\eta S V_c^2)^{-0.5}$
1993	H. Maeda et al.	$Q_p = k_2 \cdot f \cdot t_p \cdot (\eta V_c^2)^{-0.5}$
1994	M.M.Wolf	$Q_p = k_4 L_m \cdot (T_0/T_m)(S/f)^{-0.25} \eta^{-0.5} V_c^{-1.25}$
1995	H. Yasunaka et al.	$Q_p = 0.070/\eta_1 - 0.92 \log T_m + 0.52/V_c + 0.11S - 8.93 \log f + 2.79$
1998	K. Tsutsumi et al.	$Q_p = k_3 S^{0.4} T_{CS}^{-1.6} (\eta V_c^2)^{-0.5} \cos^{-1}(-1000V_c/\pi f S)$

Q_p : mold powder consumption rate (kg/m²), q_p : mold powder consumption rate per one cycle (kg/m cycle), T_m : powder melting temp. ($\approx$ breakpoint) ($^{\circ}$ C), T_{CS} : crystallization temp. of powder ($^{\circ}$ C), T_0 : average shell surface temp. ($^{\circ}$ C), η , η_1 : viscosity of powder at 1300 and 1250 $^{\circ}$ C, respectively (poise), η_s : viscosity of powder at liquidus temp. of steel (poise), S : mold oscillation stroke (mm), f : mold oscillation frequency (cycle/min), V_c : casting speed (m/min), t_p : positive strip time [$= (60/\pi f) \cos^{-1}(-1000V_c/\pi f S)$] (s), k_1 , k_2 , k_3 and k_4 : constant (-), L_m : effective mold length (m)

3.3. Present State of Technologies for Realizing High-speed Casting of Slab

Accidents or troubles in high-speed casting are closely related to phenomena in a mold, *i.e.*, breakout and mold powder entrapment occur in a mold. In order to perform the stable high-speed casting and improve the slab quality, many technologies have been developed as shown in Fig. 6²⁸⁾: a fine control system of molten steel level, a flow control system of spouting stream from the submerged entry nozzle (SEN), a large capacity tundish, and an intensive cooling mold. Many technologies for high-speed casting are concentrated on the mold and its surroundings.

4. Upper Limit of Casting Speed of Continuous Caster

It is difficult to quantitatively predict the upper limit of casting speed of a caster with an oscillating mold. There are a very few predictions of the upper limit of the casting speed.

Suzuki *et al.*²⁹⁾ predicted the upper limit of casting speed in a continuous caster with an oscillating mold by comparing the frictional force between a shell and a mold wall with the fracture strength of the solidifying shell at the initial stage of solidification in a mold. Hence, they measured *in-situ* the fracture strength of solidifying shell using a method similar to "Submerged Split Chill Tensile test" (hereafter SSCT test) which Ackermann *et al.*³⁰⁾ developed. The fracture strength of low carbon steels and peritectic medium carbon steels is shown in Figs. 7(a) and 7(b),²⁹⁾ against the average temperature of the shell determined by the solidification temperature and the interfacial temperature of the shell touching the chill block. In the figures, the fracture strength measured with the *in-situ* melting and solidified tensile test³²⁾ (hereafter *in-situ* MST test) are com-

Fig. 6. Technologies developed for realization of high-speed casting.²⁸⁾

pared with those of SSCT test. The fracture strength is approximately 1 to 3.5 MPa for an initial solidifying shell (shell thickness=2 to 5 mm), and increases gradually with decreasing shell temperature. On the other hand, the fracture strength by the *in-situ* MST test increases steeply with decreasing temperature. Furthermore, the fracture strengths by the SSCT test are smaller than those by the *in-situ* MST test. The reason of smaller strength by SSCT test than that by the *in-situ* MST test is thought that in SSCT test columnar dendrites were directed perpendicular to the tensile direction and cracks propagated in interdendritic region, whereas in the *in-situ* MST test the dendrites were grown parallel to the tensile direction.

The lubrication between a shell and a mold wall begins to be worse with increasing casting speed. The frictional force can be thought equal to the shear force of mold powder film infiltrated into a shell/mold gap,³¹⁾ and the total

Fig. 7. Fracture strength measured by a submerged split chill tensile (SSCT) test and a melting-solidified tensile (MST) test. [(a) for low carbon Al killed steels, (b) for peritectic medium carbon steels]²⁹⁾

frictional force, F_f , is a sum of the shear force throughout a whole mold, given as

$$F_f = 2(w+d) \int_{z=0}^z f_\ell dz = 2(w+d) \int_{z=0}^z \left(\eta_\ell \frac{\Delta V_m}{\Delta x} \right) dz \dots (1)$$

where w is the width, d is the thickness of a mold, z is the distance from the meniscus, f_ℓ is the frictional force per unit interfacial area, η_ℓ is the viscosity of mold powder film and $\Delta V_m / \Delta x$ is the velocity gradient of the infiltrated powder film.

This equation is valid in the case of Newtonian fluid. In a high-speed casting over 2 m/min, the frictional force is increased with casting speed, and the predicted frictional force by Eq. (1) is in good agreement with the observation as shown in Fig. 8.³³⁾ Both the observed and the predicted frictional force are adopted at the maximum relative speed between the mold oscillating speed and the casting speed. Accordingly, the frictional force calculated from Eq. (1) is thought to act throughout a mold.

Sorimachi *et al.*,³⁴⁾ however, investigated the lubrication behavior of mold powder intervened into a gap between a cooled copper plate and a hot steel disc in a laboratory test. They claimed that the frictional force is not dominated by Newtonian fluid flow, and the mold powder film in a shell/mold gap behaves like a non-Newtonian fluid.

Fig. 8. Effect of the casting speed on the frictional force between a solidifying shell and a mold wall.³³⁾

Fig. 9. Upper limit of casting speed determined by comparing the friction induced tensile force with the fracture strength.²⁹⁾

The fracture strength of solidifying shell is compared with the predicted tensile force caused by frictional force. The fracture strength is obtained from the results of SSCT test and the frictional force is calculated at the maximum relative velocity between the mold oscillating velocity and the casting speed. The fracture strength and the friction induced tensile force for 0.04 mass% carbon steel are shown in Fig. 9²⁹⁾ against the casting speed and the both are compared. At a casting speed of 8.5 m/min, the tensile force intersects the fracture strength. Thus, the upper limit of the casting speed in a caster with an oscillating mold is considered to be 8.5 m/min. This limit might be changed when a very low viscosity mold powder or a different lubricant is used. In fact, a high-speed casting of 14.5 m/min³⁵⁾ was reported to be carried out by using rapeseed oil as a lubricant with a billet caster with a cross-section of 50 mm $\times$ 50 mm at Barrow No. 2 caster, British Steel.

5. Reasons for Restraining the Casting speed at the Present level

5.1. Constraint of Casting Speed Due to Machine Length

The thickness, D_s , of solidifying shell is experimentally expressed as $D_s = K\sqrt{t}$. The average value of the solidification constant, K , throughout a caster is estimated 26 and 29 mm/min^{1/2} (36) for the mild and the intensive secondary cooling pattern, respectively. When the slab thickness is given, the solidification time, t_e , that the solidification is fully completed at the centerline of slab thickness, is calculated, and the maximum casting speed, V_{max} , is given from the machine length, L , as follows: $V_{max} = L/t_e$.

The machine length of slab casters is shown in Table 1. The machine length of the slab casters built several years ago is about 50 m. The casting speed of 3 m/min is successful in the slab caster with a thickness of 220 mm.³⁷⁾ The maximum casting speed is predicted approximately 3.2 m/min of the slab caster with a machine length of 49 m.

5.2. Constraint of Casting Speed Due to Slab Quality

5.2.1. Constraint Due to Slab Surface Cracking

Kanazawa *et al.*³⁸⁾ carried out a high-speed casting test with a 90 mm thick slab caster. They measured temperatures in the copper plate mold and predicted the local heat flux. The relationship between the local heat flux in the mold and the frequency of longitudinal facial crack formation is shown in Fig. 10³⁸⁾ for low carbon Al killed steel and peritectic medium carbon steel. They found out that the critical local heat flux for formation of the longitudinal crack are approximately 2.8×10^6 W/m² and 1.7×10^6 W/m² for the low carbon steel slabs and the peritectic medium carbon steel slabs, respectively. However, they did not explain the reasons for the existence of the critical heat flux for formation of the longitudinal facial crack and the dependence of the critical one on the steel grade.

For the conventional slab casters, Osanai *et al.*,³⁹⁾ Ebato *et al.*⁴⁰⁾ and Watanabe *et al.*⁴¹⁾ were successful in producing longitudinal crack free slabs of peritectic medium carbon steel at a casting speed of 2 m/min, improving the mold powder characteristics and the secondary cooling pattern.

On the other hand, transverse crack is one of serious surface cracks to be prevented. This crack formation is caused by the embrittlement of steel in the temperature range of 750 to 950°C.⁴²⁾ Temperatures in a slab are increased with increasing casting speed. At high-speed casting, since a slab attains higher temperatures than the embrittlement temperatures, the transverse cracks are not formed.

5.2.2. Constraint Due to Alumina Inclusions and Mold Powder Entrapment

(1) Endogenous Inclusions in Molten Steel

Most inclusions in steel are deoxidation products, *i.e.*, alumina, and some technologies for removing alumina particles have been developed.

When a liquid slag in a LD converter is flown out to a ladle on tapping, since iron oxide content in the slag is high, molten steel deoxidized with aluminum is reoxidized by the slag. Resultantly, a large amount of alumina is formed in the molten steel. Accordingly, the slag in a ladle is removed intentionally and a different refining flux is

Fig. 10. Critical local heat flux for formation of a longitudinal facial crack for low carbon Al killed steel and peritectic medium carbon steel.³⁸⁾

Fig. 11. Effect of the tundish volume and the width/depth ratio on the outflow ratio of inclusions calculated by a computer simulation.⁴⁴⁾

added into the ladle and the iron oxide content in the slag⁴³⁾ is adjusted as low as possible. This treatment can reduce the amount of formation of alumina particles. In addition, in RH degasser a longer circulation time treatment is performed to remove inclusion particles. In tundish the reoxidation should be prevented completely. During transferring molten steel from ladle to tundish, and from tundish to mold, air suction should be prevented at a gap between sliding valve plates or connecting plates of a shrouding tube and a SEN.

Computer simulation of molten steel flow in a tundish can give trajectories of inclusion particles and estimate the effect of tundish capacity on the removal rate of inclusion particles. Nakaoka *et al.*⁴⁴⁾ performed the computer simulation and a water model experiment and showed that the effect of tundish capacity and its shape on the removal rate of inclusions as shown in Fig. 11.⁴⁴⁾ The larger capacity, the wider width and the shallower depth of tundish can remove the inclusion particles more effectively.

(2) Exogenous Inclusions in Molten Steel

The mold powder entrapment is one of most serious inclusion problems. Since the mold powder is engulfed in the subsurface of a slab, the entrapped mold powder causes

several kinds of surface and internal defects of steel products, *e.g.*, a sliver and a scab on steel sheets and a flange crack of deep drawing ironing (DI) cans. The frequency of mold powder entrapment is increased with casting speed. This shows that the mold powder entrapment heavily deteriorates the quality of steel sheets and plates. Hence, many researchers have great interest in the prevention of mold powder entrapment. Many papers have been published on the countermeasures for prevention of the mold powder en-

trapment.

Some researchers⁴⁵⁻⁵²⁾ investigated the phenomena of mold powder entrapment with a water model experiment. The water model experiment can show that the mold powder begins to be suspended into water pool caused by two mechanisms as shown in **Figs. 12(a)** and **12(b)**. One is shown in Fig. 12(a) where the strong surface flow tears the particles off near the water/particle interface simulating the molten steel/powder interface. The other is in Fig. 12(b) where a vortex formed near a submerged entry nozzle (SEN) sucks the particles and forms droplets into the interior of water pool. Tanaka *et al.*⁴⁷⁾ presumed the causes of mold powder entrapment phenomena as follows

- (1) Karman's vortex formed near the SEN sucks the mold powder covering the surface of molten steel in the mold.
- (2) High shear stress between the molten steel flow reflected from the narrow face and the mold powder induces a shear flow instability, which causes the entrapment on the mold powder.
- (3) Argon gas injected into the SEN for preventing the build-up of alumina particles on the inner wall of the SEN attacks the molten steel/mold powder interface, which causes the mold powder entrapment.

The criteria corresponding to mechanisms for formation of the mold powder entrapment are summarized in **Table 3**.

Otsuka *et al.*⁴⁹⁾ presented the mechanism that surface flow tears mold powder off and forms droplets in molten steel pool. They gave the critical surface velocity of molten steel for formation of the mold powder droplets as shown in **Fig. 13** after modifying Asai's proposed analysis⁵³⁾ for entrapping the liquid slag droplets into the molten steel pool with Ar gas bubbling in a ladle. When Ar gas bubbles pass through the interface between the molten steel and the liq-

Fig. 12. Mold powder entrapment caused by (a) shear force of surface stream and (b) vortex formation (water model experiment).

Table 3. Mechanism of the mold powder entrapment and its critical condition.

Mechanism	Causes	Researcher	Critical conditions	Experimental method	Ref.
Suction of mold powder by Karmen's vortex	Biased surface flow of molten steel in one side of SEN	Tanaka <i>et al.</i>	Vortex depth, H_v : $H_v = (\rho_m \alpha^2 / 2g) (U_1^2 / L) / (\rho_m - \rho_p)$	Water/silicon oil model	(47)
		Yamaoka <i>et al.</i>	No entrapment: $V_s + 2.14U_d < 15$ (V_s : surface velocity, U_d : downward velocity near the SEN)	Water/polyethylene particle model	(50)
		Watanabe <i>et al.</i>	Critical submergence, L_c : $L_c = 8.58\eta^{-0.0886} \cdot \gamma^{-0.0552}$ (γ : water/oil interfacial tension)	Water/silicon oil	(63)
Slag drop formed by shear force due to surface stream	Higher surface velocity and larger level fluctuation of surface stream	Imamura <i>et al.</i>	No entrapment: $V_s < 15\text{cm/s}$	Water model and actual casting	(46)
		Yamazaki <i>et al.</i>	No entrapment: $V_s < 20\text{cm/s}$ (no dependence of viscosity)	Water/silicon oil model	(52)
		Yamaoka <i>et al.</i>	No entrapment: $V_s < 15\text{cm/s}$ (dependence of viscosity)	Water/silicon oil model	(50)
		Ootsuka <i>et al.</i>	Modification of Asai's analysis	Water/silicon oil model	(49)
		Kasai <i>et al.</i>	No entrapment: $V_s < [2\sqrt{12(\rho_m - \rho_p) \cdot g \cdot \sigma / \rho_p - 2gH}]^{1/2}$	Water /silicon oil model	(48)
		Iguchi <i>et al.</i>	Milne-Thompson criteria: $(V_{1cr} - V_{2cr})^2 = (\rho_2 - \rho_1)g(H_1 / \rho_1 + H_2 / \rho_2)$ (no dependence of viscosity)	Water/silicon oil model	(54)
		Teshima <i>et al.</i>	F-value: $F = \rho Q_V (1 - \sin \theta) / (4D)$ Optimum range: $1.7 < F < 3$	Water model and actual casting	(63)
Turbulence of mold powder/ molten steel interface by Ar bubbles	Ar gas passing through mold powder/molten steel interface	—	—	—

Fig. 13. Analytical model for mold powder entrapment.

uid slag, the molten steel and the interface moves violently. This turbulent motion forms many slag droplets in the molten steel pool. The potential energy balance for formation of a spherical slag droplet is described as

$$\frac{1}{2} \rho_p \cdot \left(\frac{4}{3} \pi R_p^3 \right) \cdot V_s^2 + g H \rho_p \cdot \left(\frac{4}{3} \pi R_p^3 \right) \geq 4 \pi R_p^2 \sigma + g (\rho_m + \rho_p) \cdot \frac{4}{3} \pi R_p^3 \cdot R_p + \eta \left(\frac{\Delta U}{\Delta z} \right)^2 \cdot A_p \quad \dots (2)$$

where V_s is the surface velocity of molten steel, H : the level fluctuation, g is the gravity acceleration, ρ_m and ρ_p are the densities of molten steel and mold powder, R_p is the radius of powder slag droplet, σ is the interfacial energy between molten steel and powder, η is the viscosity of powder, $\Delta U/\Delta z$ is the velocity gradient in the powder within the velocity boundary layer, which is assumed equal to $V_s/2R_p$, and A_p is the contact area ($=2\pi R_p^2$) between powder drop and molten steel.

The first term in the left side of Eq. (2) is the kinetic energy of a slag droplet, the second is the potential energy, and in the right side the first is the interface formation energy, the second is the potential energy due to a buoyancy force, and the third is the dispersion energy by viscous fluid.

When a mold powder droplet is formed, the discriminant of Eq. (2), which is a function of the surface velocity, V_s , and the level fluctuation, H , should be greater than zero, i.e., this means that a solution of R_p is a real number in Eq. (2). The calculated relationship between V_s and H is shown in Fig. 14 as a parameter of viscosity of mold powder. The validity of this relationship was confirmed with a water model experiment. We can observe that silicon oil is torn off by a water flow below the water/oil interface, and formed to small droplets, then the droplets suspend into the water pool. The observation is in good agreement with the prediction in Fig. 14. This model can give the critical curves of surface velocity vs. the level fluctuation for formation of the mold powder entrapment. The higher viscosity mold powder is more effective to prevent the mold powder entrapment, i.e., it can extend the critical range of the surface velocity and the level fluctuation to a wider range.

Kasai *et al.*⁴⁸⁾ and Yamaoka *et al.*⁵⁰⁾ performed water model experiments similar to Otsuka's one,⁴⁹⁾ and gave the critical surface velocity of 15 cm/s and 20 cm/s, respectively. The two experiments gave the dependence of the viscosity on the critical surface velocity; on the contrary, a water

Fig. 14. Observation of water model experiment and calculated critical curves for formation of mold powder entrapment between surface velocity and level fluctuation.⁵⁰⁾

model experiment with one-fifth size by Yamazaki *et al.*⁵²⁾ showed that the entrapment initiates over 20 cm/s irrespective of viscosity of silicon oils. Iguchi *et al.*⁵⁴⁾ investigated the mold powder entrapment caused by shear flow instability of molten steel near the meniscus with a water model experiment where silicon/salt water interface is moved violently by inclining a water pool, and explained the phenomena using Kelvin–Helmholtz instability. The original theory on Kelvin–Helmholtz instability is concerned with a shear flow instability occurring at an interface between two horizontal liquid layers extending infinitely. Kelvin–Helmholtz instability implies that the interfacial energy and the density of molten steel and mold powder affect the critical velocity difference giving the beginning of the mold powder entrapment.

A difference of the critical velocity for formation of Kelvin–Helmholtz instability in a flow field was given by Milne and Tompson as

$$(V_{1cr} - V_{2cr})^2 = (\rho_2 - \rho_1)g(H_1/\rho_1 + H_2/\rho_2) \quad \dots (3)$$

where ρ_1 and ρ_2 are the density of the upper and the lower liquid, g is the acceleration due to gravity, H_1 and H_2 are the thickness of equivalent velocity layer in the upper and the lower liquid, and V_{1cr} and V_{2cr} are the critical velocity in the upper and the lower layer. Iguchi's result showed that the mold powder entrapment occurs over 20 cm/s and does not depend on the viscosity of silicon oils similar to Yamazaki's result.⁵²⁾

Thus, we have a good agreement with the critical surface velocity for formation of the mold powder entrapment, but do not have an agreement with the effect of viscosity of mold powder.

Mukai *et al.*⁵⁵⁾ studied the influence of Ar gas injection and the wettability between the water and the SEN on the mold powder entrapment by means of a silicon oil–water experiment. They changed the wettability by coating a wax on the SEN wall. They found out that Ar gas affects the entrapment of silicon oil by giving rise to a strong fluctuation on the water/silicon oil interface simulating the molten steel/mold powder interface in a mold. As shown in Fig. 15,⁵⁵⁾ they showed that the critical flow rate of water is de-

Fig. 15. Influence of wettability on the entrapment of silicon oil (water/silicon oil model).⁵⁵⁾

creased with increasing flow rate of gas. The critical flow rate in the case of a poor wettability between the water and the SEN is also lowered more comparing with that in the case of good wettability. Since the wettability between the SEN and Ar gas is thought poor similar to that between porous refractory coated with a wax film and Ar gas, the entrapment tends to more frequently occur in the actual casting mold.

6. Research Issues for High-speed Conventional Slab Casting in the Future

6.1. Uniform Shell Formation in Continuous Casting Mold

Figure 16 shows a comparison of casting speed between the actual operation and the prediction. As aforementioned, the predicted upper limit of casting speed seems to be approximately 8.5 m/min. Recently Kikuchi *et al.*⁵⁶⁾ succeeded in an ultra high speed casting of 8 m/min with a medium thickness slab caster. However, the practical casting speed in the conventional slab caster is less than 3 m/min for low carbon Al killed steel, and less than 2 m/min for peritectic medium carbon steel. To reduce the difference of casting speed between the practice and the prediction is one of issues in the continuous casting technology. The predicted upper limit of casting speed depends on the shell strength and the lubrication in the mold. The shell strength is influenced by the cooling conditions in the mold, and the lubrication is affected by the mold powder characteristics. If the shell strength is increased, and the frictional force is lowered more than the present level, the casting speed will be increased higher.

Solidification constant in a continuous casting (CC) mold was obtained with a tracer addition test. The result shows that the solidification constant ranges from 18 to 22 mm/min^{1/2}.²⁵⁾ On the other hands, when the temperature of shell at the shell/mold wall interface is remained constant, the solidification constant, K , is given theoretically as⁵⁷⁾

$$\frac{K}{2\sqrt{\alpha}} \exp\left(\frac{K^2}{4\alpha}\right) \operatorname{erf}\left(\frac{K}{2\sqrt{\alpha}}\right) = (T_m - T_s) \frac{C_p}{H_f \sqrt{\pi}} \quad \dots(4)$$

Fig. 16. Comparison of casting speed between the actual operation and the prediction.

Fig. 17. Solidification constant, i.e., K -factor, in the mold.²⁶⁾

Substituting the values of physical properties⁵⁸⁾ such as the thermal diffusivity, α ($=0.624 \times 10^{-5} \text{ m}^2/\text{s}$), the specific heat capacity, C_p ($=0.67 \text{ kJ/kg K}$), of shell, the latent heat, H_f ($=272 \text{ kJ/kg}$), the melting temperature, T_m ($=1530^\circ\text{C}$), and the interfacial temperature, T_s ($=1000^\circ\text{C}$), into Eq. (4), we get a solidification constant, K , of approximately 25 mm/min^{1/2}. This value implies an upper limit in a CC mold.

A problem on the solidification in a mold is nonuniformity of shell formation. As shown in Fig. 17,²⁶⁾ the solidification constant has a large scatter in the direction of mold width. This test shows that an improved mold powder can form more uniform shell comparing with that by the conventional mold powder. Uniform shell formation is effective to reduce the frequency of the breakouts and the surface cracks formed at a thinner part of shell. It is very important to form uniform thickness of the shell along the periphery of a mold. Therefore, we should control the heat transfer uniformly along the periphery of a mold. Thermal resistance in a mold is analyzed as shown in Fig. 18.⁵⁹⁾

(a) Temperature distribution

(b) Thermal resistance between the solidification front and the cooling channel in the mold copper plate

 Fig. 18. Thermal resistances from molten steel to cooling channel in continuous casting mold.⁵⁸⁾

This result shows that thermal resistances due to the thickness of mold powder film and the mold powder film/mold wall interface are larger than those due to the shell thickness, the mold plate thickness, the molten steel flow at the solidification front and the water stream in a cooling channel of the mold. We can find out that the quality of the mold powder film strongly affect the shell formation in the mold. In order to form a uniform mold powder film along the periphery of the mold, we should control the uniform infiltration of the mold powder into a mold/shell gap and obtain the uniformity of heat transfer in the direction of the mold width.

Measures for prevention of the longitudinal crack are given in Fig. 19. At low-speed casting longitudinal cracks are not apt to be formed. At high-speed casting, reducing the heat flux less than the critical value is one of the preventive measures by improving the mold powder characteristics. The other is to form the uniform solidifying shell.

6.2. Endogenous Inclusions in Molten Steel

The important technologies shared with the conventional slab caster, the thin slab caster and the twin roll strip caster

Fig. 19. Measures for prevention of longitudinal crack of peritectic medium carbon steel.

are considered as follows: casting of clean steel, pouring of molten steel into a mold, and prevention of the mold powder entrapment.

Inclusion problem is relating to both refining and casting processes. There are technologies that inclusion particles are intentionally coagulated with a magnetohydrodynamic flow in a tundish, which is developed by Miki *et al.*,⁶⁰⁾ called Centrifugal Magnetic Field Tundish. However, since the inclusion particles can be removed fully with a secondary refining process such as Ar gas bubbling in a ladle or RH degasser treatment before pouring molten steel into the mold, the inclusion problem is not essential to perform high-speed casting.

6.3. Prevention of Build-up of Alumina Particles in Submerged Entry Nozzle

A pouring system of molten steel from tundish to mold with the SEN is one of common technologies in the three casting processes. When the SEN is used, free surface of molten steel is formed in the mold, and a molten steel flow occurs in the strand caused by a spouting stream from the SEN. The strong molten steel flow near the meniscus causes the mold powder entrapment.

Fine alumina particles in molten steel also are deposited on an inner wall of the SEN during molten steel flowing through the SEN. If the alumina particles in deposit will be peeled off, flown into the mold, and engulfed by solidifying shell, they deteriorates the slab quality. The alumina build-up also decreases the flow rate of molten steel from tundish to mold and disturbs high-speed casting.

Ogibayashi⁶¹⁾ reviewed mechanism of alumina build-up on the inner wall of the SEN and its countermeasures. He summarized the mechanism of alumina build-up as follows:

- ① The origins of oxides deposited on the inner wall of the SEN are alumina particles suspending in molten steel, which are deoxidation products
- ② The movement and the adhesion of fine alumina particles in molten steel to the inner wall of the SEN caused by the inertial force of the micro vortex formed in the vicinity of the inner wall
- ③ The adhesion of alumina particles to the SEN wall is that clustering is formed due to reduction of the interfacial energy, and subsequently sintering is taken place.

Countermeasures to prevent the alumina build-up are: ① lowering the melting temperature of the deposit by changing deoxidation alloys, *e.g.*, Ca-addition treatment, ② cleanliness of molten steel (reduction of the amount of inclusions), ③ Ar gas injection into the SEN, ④ prevention of

Fig. 20. Measures for prevention of the mold powder entrapment.

the solidification of molten steel, and ⑤ lowering the melting temperature of the deposit by the reaction of the deposited alumina particles and the SEN material at the SEN/deposited alumina interface. The fifth among these countermeasures is most important.

Tsujino *et al.*⁶²⁾ analyzed the dissolution reaction between SiO_2 particles and graphite (C) contained in the SEN material, and the generation rate of alumina due to the reaction between the oxygen gas caused by the dissolution of SiO_2 particle and soluble aluminum in molten steel. They showed that at the early stage of alumina build-up, the alumina particles are deposited as a network-shape on the SEN wall. Subsequently, the alumina particles in molten steel collide with the network-shaped alumina formed on the SEN and deposited. They claimed that once an alumina particle enters into the concentration boundary layer near the SEN wall, it is forced to move to the SEN wall by the attractive force due to the interfacial energy gradient formed by concentration gradient of solute elements such as carbon and silicon.

6.4. Prevention of Mold Powder Entrapment

Measures to prevent the mold powder entrapment are summarized in Fig. 20. Each measure is described as follows.

6.4.1. Improvement of Mold Powder

The surface velocity or the level fluctuation of molten steel in a mold is increased with casting speed.⁶⁴⁾ The above mentioned mechanisms of the mold powder entrapment show that there exist the critical values of the surface velocity and the level fluctuation of molten steel. Accordingly, the higher viscosity mold powder can extend to wider range of the surface velocity and the level fluctuation (measure ① in Fig. 20). However, the mold powder consumption rate is decreased with increasing viscosity of mold powder. The higher viscosity mold powder makes poor lubrication and increases the frequency of sticker breakouts.

K. Watanabe *et al.*⁶³⁾ investigated the effect of the viscosity and the interfacial energy between the mold powder and the molten steel on the entrapment caused by suction with a

water model experiment and a hot model experiment with molten steel. They dipped a J-shape tube into a liquid to a certain depth across the oil layer or the mold powder layer placed on the liquid surface, and subsequently sucked the liquid. After pulling the J-shape tube out of the liquid pool, they investigated whether the components of the oil or the mold powder were detected in the sucked liquid or not. Performing these experiments, they measured the critical submergence, *i.e.*, the immersion depth of the J-shape tube from the water/oil or the molten steel/mold powder interface that the oil or the mold powder begins to be sucked into the tube or not. Their result shows that the viscosity and the interfacial energy have great influence on the mold powder suction, and that the higher interfacial energy is more effective to prevent the mold powder suction similar to the effect of viscosity. However, it is difficult to change the interfacial energy of a practical mold powder, because most steels cast with the continuous casters are Al killed steels, and the soluble oxygen concentration in steel is negligible and the sulfur concentration is adjusted about 0.01 mass%. In addition, the mold powder is composed of CaO , SiO_2 , Al_2O_3 and CaF_2 and its composition is nearly the same irrespective of different mold powders. Accordingly, we cannot easily adjust the interfacial energy of the mold powder. Resultantly a practical measure is to increase the viscosity for prevention of the mold powder entrapment.

6.4.2. Optimization of Molten Steel Flow in Mold

T. Teshima *et al.*⁶⁴⁾ analyzed the flow pattern in the mold with a water model experiment. They found out that the spouting stream from the SEN collides with the narrow face shell, and is divided into an upward and a downward stream, the upward stream along the narrow face shell strongly affects the mold powder entrapment. They elaborated an index of the intensity of kinetic energy of the upward stream, which is called *F*-value, and defined as

$$F = \frac{\rho \cdot Q_v \cdot V_d \cdot (1 - \sin \theta_c)}{4L_d} \dots \dots \dots (5)$$

where ρ is the density (kg/m^3) of molten steel, Q_v is the volumetric casting rate (m^3/s), V_d is the velocity (m/s) of spouting stream at the collision with narrow face shell, θ_c is the collision angle (deg.) of spouting stream with narrow face shell, and L_d is the collision depth (m) of spouting stream from the meniscus.

They found out that the optimum F -value resulted in 1.7 to 3 in order to suppress the surface velocity of molten steel flow. Controlling the F -value the optimum range by changing the casting conditions: the spouting angle and the immersion depth of SEN, and the Ar gas flow rate, they succeeded in reduction of the defects in continuously cast slab caused by the mold powder entrapment. In addition, this index " F -value" is combined with the electromagnetic brake with a travelling magnetic field, and is used to reduce the defects caused by the mold powder entrapment.

6.4.3. Control of Molten Steel Flow in Mold by Electromagnetic Force

Controlling the molten steel flow in the mold is essential to produce a good quality slab. At present we have some technologies to control the molten steel flow in the mold, most familiar technology is an electromagnetic brake (EMBR)⁶⁵ for the first time developed in cooperation with ASEA and Kawasaki Steel Corp. In this original model, a static magnetic field was used, and the magnetic field is imposed perpendicularly to the spouting stream. After then Yamaguchi *et al.*⁶⁶ have developed a new EMBR, *i.e.*, a double magnetic field imposed in the area above and under the spouting stream. Ishii, *et al.*⁶⁷ also developed a uniform static magnetic field covering the whole width of mold. Such a braking force is effective to suppress the surface velocity of the molten steel caused by the upward stream and shallow an invading depth of the downward stream into the strand (measure ⑧ in Fig. 20).

On the other hand, Kubota *et al.*⁶⁸ developed a different technique of flow control of molten steel in a mold with a linear motor type electromagnetic stirrer (M-EMS). The stirrer can act a braking or an accelerating force to the spouting stream by using a travelling magnetic field. At high-speed casting the braking force is generated when the travelling magnetic field is moved against the spouting stream, whereas at low-speed casting, *e.g.*, during the ladle switching, the accelerating force is formed when the travelling magnetic field is moved along the spouting stream.

Ohtani *et al.*⁶⁹ used the M-EMS as a stirrer. This stirrer can move molten steel strongly at the solidification front. They found out that the flow induced by the M-EMS prevents inclusion particles from being engulfed by the solidifying shell.

In the electromagnetic braking technology developed, a constant intensity of magnetic force is imposed to the spouting stream when the casting conditions, *i.e.*, the casting speed, the slab size (width and thickness), the SEN and the flow rate of Ar gas, are not changed.

However, when the larger level fluctuation suddenly happens, the more intensive magnetic force should be imposed in order to hold the level fluctuation smaller.

In the present EMBR technique, the braking force of EMBR is imposed at a constant value to the given casting conditions. In the future, the intensity should be dynamical-

Fig. 21. Technological issues developed to produce higher quality slabs in high-speed casting.

ly changed proportionately with a velocity of molten steel flow near the meniscus. Therefore, we need a monitoring system,^{70,71} *e.g.*, a mold flow monitoring system, to dynamically control a fluid flow within an optimum range by changing the intensity of braking or accelerating force of EMBR, the flow rate of Ar gas and the immersion depth of SEN. This system will produce high quality slabs and be effective to perform the stable high-speed casting.

Andrzejewski *et al.*⁷⁰ developed a system of detecting the flow pattern of molten steel in the mold during casting using a sensor named Mold Flow Control (MFC) sensor, which consists of permanent magnets and high sensitive detectors and was installed into a mold. They grouped the flow pattern of molten steel three patterns and would predict whether the mold powder entrapment is formed or not using the relationship between the observed flow pattern and the quality of the final product.

As aforementioned, some issues that we should develop to produce higher quality slab in high-speed casting are summarized in Fig. 21.

7. Conclusions

The casting speed of the conventional slab continuous casters was increased stepwise 1 to 2 m/min level two decades ago. However, after that times the casting speed has been remained about 2 m/min level. The reasons for constraining the casting speed are discussed.

Resultantly the constraints are thought slab quality problems: the mold powder entrapment of low carbon and ultra low carbon steels, and the formation of longitudinal facial crack of peritectic medium carbon steel.

A pouring system of molten steel with a submerged entry nozzle from tundish to mold and powder casting are common technologies to the conventional slab caster and the thin slab caster. Accordingly, some of research issues in high-speed casting are problems caused by the pouring system and the powder casting, *i.e.*, the build-up of alumina

particles in a submerged entry nozzle and the mold powder entrapment. The measures to improve quality of conventional slabs at high-speed casting over 4 m/min are discussed.

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