Re-start Technology for Reducing Sticking-type Breakout in Thin Slab Caster

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In order to increase the production rates and to secure the base production technology for the hard casting materials, a re-start casting technology as an active curing methodology has been developed to reduce the number of sticking type breakouts in the thin slab caster with high speed. It consists of the healing casting conditions of breakouts, the mold level control method for preventing the overflow or big change of molten steel near meniscus and the control of cooling rate at second cooling zone for rolling under the limits of rolling force and torque at the directly linked roughing mill. By applying the proposed technology, the automatic restarting rate of breakout is remarkably increased from 0 to 92%.

KEY WORDS: sticking-type breakout; thin slab casting; recovery methodology; mold level control.

1. Introduction

Figure 1 shows the schematic diagram of Kwangyang No. 1 Mini-Mill (or TSMP: Thin Slab Mill Process). POSCO has constructed it with a production capacity of 1.8 million ton of steel per year in Kwangyang, South Korea and started the operation in August, 1996. The thin slab caster, which needs the highest techniques of the Mini-Mill plant, has the parallel mold with the dimension of 900–1350 mm width×75 mm thickness and the resonance mold which consists of the spring and the servo-hydraulic system.¹ The maximum casting speed is designed to be 5.0 m/min.

In the process, the molten steel in tundish is poured into the mold through submerged entry nozzle and is solidified by the heat transfer into the mold. Then, it is continuously cooled down by the secondary cooling units and shaped into slabs. After the solidifying slab is softly reduced, it is rolled by the roughing mills to the specified thickness. The rolled strip then is coiled before it is moved to the reheating units. After that, it is rolled again in the Finishing Mill (It is not shown in Fig. 1).

At that time, the solidified shell is continuously withdrawn out of the mold synchronized with the casting speed. Since the solidified shell at the mold exit acts as supporting vessel, the uniform solidification layer is indispensable for...
good quality slab.

However, as shown in the Fig. 2, the unsteady heat transfer phenomenon around the molten steel surface makes the solidification layer stick to the mold and this allows non-uniform solidification. Then it is separating from the normal shell and the molten steel is starting to leak from the breakage at the exit of mold. And if the steel pressure is concentrated on that point, non-solidified steel is continuously flowing out from it. Then this makes the casting impossible and it is called as breakout.

In order to detect the time of breakout in advance, the BOPS (Break-Out Prediction System) is normally adapted and is operating in the field. Its main decision is based on the temperature signals from sensors embedded in the mold. When the BOPS warning is generated, the speed down is accompanied by manually or automatically.2)

In general, the conventional continuous casting is performed at lower speed below 2 m/min. Thus the curing action by manual speed-down is possible after breakout warning.3) Therefore, there have been research activities to understand the formation mechanism of the sticking type breakouts and develop the BOPS system.3–5)

However, it is impossible to cure manually in POSCO’s thin slab caster because the time required for curing is too short from high casting speed (over 4 m/min). Though the number of breakout had been reduced in low-carbon steel after the introduction of BOPS, it was not very effective in reducing breakouts of the hard-casting materials such as medium-carbon steel, high carbon steel, etc. This limits POSCO making new profit in the process. In this respect, in order to increase the production rate and secure the casting quality slab.

In this paper, as a systematic approach for development of the healing casting conditions of breakouts, the formation mechanism of sticking-type breakout by Mills4) is studied to understand the breakout logically. Also, the mathematical equations proposed by Tsuneoka5) in the continuous caster are used to explain the repairing mechanism of rupture. Then, the recovery limit conditions of sticking-type breakout in the thin slab caster with high speed are derived based on the equations. Finally, the admissible casting conditions are found from the effects of various casting conditions (such as the decelerating slope of speed, the minimum speed, the holding time of minimum speed, increasing slope of speed) on the solidification time, shell thickness and necessary condition value for curing.

When the proposed healing conditions are applied to real-situation, two major problems can be occurred. One is the rolling motor trip due to its rolling torque limitation due to the over-cooling in the secondary cooling zone. The other one is more severe than that of the first one. From the abrupt speed changes during the curing process, the overflowing of molten steel from the mold or big mold level oscillations is observed. These result in casting stop situation. As casting speed is sharply decreased, the outflow mass from the mold is reduced as the same proportion. In this case, if the mold level controller is not properly reducing the inflow into mold, the surplus mass is over-flowing from the mold. In other way, since the operating point is changing as the speed is varying, a non-intelligent controller may promote big mold level variation. All these are serious accident and can damage both machine and/or human operators. To solve these problems, the modification of cooling control pattern and new mold level control functions are developed.6)

In brief, the proposed method resorts to an active curing methodology which is based on the pre-calculated casting speed changes and the cooling water adjustment with the help of excellent mold level control. The healing sequences are as follows: BOPS predicts the breakout in advance and send alarm signal to the speed control unit and the cooling control unit. Then the speed controller is decelerating rapidly to nearly zero speed so that the sticking point is recovered to the normal shell before it goes out of the mold exit. Whereas the cooling control unit properly adjusts the cooling rate of secondary cooling zone according to the speed changes. After the sticking point is cured, the speed is ramped up again to normal value and the casting is continued. The important thing is that the time required for curing process should be minimized to prevent over-cooling.

The proposed re-start method for reducing breakout had been implemented on the POSCO’s thin slab casting plant and the results of operations was very successful. The automatic restarting rate is remarkably increased from 0 to 92% and the anticipated profit will be 6.14 million dollars per year from the decrease of casting suspension, the productions of high-valued steel, etc.

2. BOPS Technology

BOPS is the system which predicts the breakout in advance and its main information is based on the temperature signals from sensors embedded in the mold.2) The BOPS warning is normally generated after 4th stage of the Fig. 2. Then the speed down is accompanied by manually or automatically. This helps the ruptured shell bonded to the lower shell and the casting continues without interruption. In Fig. 3, (a) shows thermocouples inserted in the mold and (b) shows real installations in the mold. Thermocouples can be installed as matrix type if needed but maintenance and cost will be problems.

Normally, two or three rows of thermocouples are inserted into the mold to measure the temperature profile and BOPS checks trends of sensor outputs to determine the
breakout. The typical temperature pattern in case of breakout is shown in Fig. 4. The temperature is increasing as the sticking point moves to the TC (Thermo-Couple) and rapidly decreasing after short peak. The nearby sensors show similar pattern with some time-delays. The BOPS logic compares the temperature changes and sends signals to the operator when the compared pattern is matched with breakout. Then the casting speed is rapidly down according to the pre-defined forms by manually or automatically.

3. Healing Conditions of Sticking Type Breakout

3.1. Formation Mechanism of Sticking Type Breakout

As shown in Fig. 5, Mills\(^4\) reported the formation mechanism of shell sticking that a sticking type breakout is related to carbonaceous agglomerate located at meniscus and the behavior of slag rim; the carbonaceous agglomerate disturbs and interrupts the slag flow into the gap between shell and mold. It produces a carbon-rich zone that is not solidified during negative strip (negative strip is a condition that is obtained when the downward velocity of the mold exceeds the casting speed of the strand). Then a quasi-meniscus forms in the vicinity of the meniscus and separates from the actual meniscus due to re-melting of solid slag film. As casting progresses, a quasi-meniscus downwards and is not repaired in the negative strip and a tear redevelops during positive strip. Finally, breakout occurs when the sum of a friction force at the interface of mold and shell, and a withdrawal force by gravitational acceleration exceeds the shell yield strength, due to the absence of lubrication.

Also, Lu\(^5\) reported the characteristics of sticking type breakout at slab continuous caster using the propagation model and observation for breakout shell.

- The shell thickness in the rupture portion is increasing towards the meniscus, which is contrary to the case of normal shell.
- Ripple marks are V-shaped and fanning out from the sticking point.
- Either upper ripple or lower ripple pitch is smaller than that of oscillation marks.

Figure 6 shows a slab of the breakout with sticking position nearly at the mid-face of broad side in thin slab caster of POSCO. An angle of tear line is approximately 45 degree. The tear line is V-shaped and fanning out from the sticking point.

Fig. 3. Thermocouple arrangements and real installation.

Fig. 4. Typical pattern of temperature in case of breakout.

Fig. 5. Formation mechanism of sticking type breakout during mold oscillation periods proposed by Mills.\(^4\)

Fig. 6. Sticking type breakout with sticking position nearly at the mid-face of broad face.
3.2. Repairing Mechanism of Rupture

According to Tsuneoka, the mechanism of repairing the rupture in the slab continuous caster is based on the balance of forces acting on shell in the mold and shear strength of shell.

In the normal state,

- **friction force:**
  \[ F_f = \int_0^{\alpha} \mu \rho \gamma x \, dy \, dx = \frac{1}{2} \mu \rho \gamma W \gamma t^2 \]  

- **withdrawal force:**
  \[ F_g = \int_0^{\alpha} \int_0^{W} \rho_s \, dz \, dy \, dx = m \rho_s W \gamma t^{n+1} \]  

- **shell yield strength:**
  \[ F_s = \int_0^{\alpha} \int_0^{W} \sigma \alpha \, dz \, dy = m \rho \gamma W \sigma \]  

- **average yield stress:**
  \[ \bar{\sigma} = 0.118 \rho \gamma m^{2-n} - 0.0367 \text{ kgf/mm}^2 \]  

- **shell thickness:**
  \[ z = m \rho \]  

where \( \mu \) is the coefficient of friction between the mold and shell, \( \rho, \rho_s \) represent the specific gravity of shell and molten steel. \( V_\gamma, W, t \) are casting speed, slab width, time elapsed from the meniscus and \( m, n \) are solidification constants. Also, \( x, y, z \) mean the casting direction, transverse direction and the thickness direction.

**Figure 7** shows the comparison between forces on the shell in the normal and shell constraint state. When the quasi-meniscus with casting speed 4.5 m/min and \( \alpha = \beta = 0.75 \) passes 274.2 mm below meniscus, the sum of withdrawal force and shear strength is less than the friction force. Then, the rupture propagates downwards due to the friction force caused by the ferro-static pressure.

In shell sticking state as shown in Fig. 7,

- **friction force:**
  \[ F_f = 2 \int_0^\alpha \int_0^{W_\gamma} \mu \rho \gamma x \, dy \, dx = \frac{1}{2} \mu \rho \gamma W \gamma t^2 \]  

- **withdrawal force:**
  \[ F_g = \frac{4m\pi^2 f^2 s}{(n+1)(n+2)g} \]  

If the shear strength of ruptured shell is assumed to have been generated by the solidified shell formed during the negative strip period of mold oscillation and to have a maximum value at the end of the negative strip period of every oscillation, the

- **shear strength:**
  \[ F_s = 2 \int_0^{\alpha} \int_0^{W_\gamma} \tau_N \alpha \, dz \, dl = 2mlm^2 \tau_N \cos \theta \]  

where subscript “N” means the end of the negative strip period.

- **length of tear line:**
  \[ l = \sqrt{\alpha^2 + \beta^2} \, V_\gamma t \]  

- **relationship between shear stress and yield stress:**
  \[ \tau_N = \frac{\sigma_N}{\sqrt{3}} \]
• negative strip period:

\[ t_N = \frac{1}{\pi f} \left[ \frac{\pi}{2} - \sin^{-1}\left( \frac{V_\text{c}}{\pi f s} \right) \right] \].............(8)

• angle of tear line: \( \theta = \tan^{-1}\left( \frac{\beta}{\alpha} \right) \)

• oscillation frequency: \( f = \gamma V_\text{c} \)

• position of quasi-meniscus before decreasing speed: \( x = \alpha V_\text{c} t \)

during decreasing speed: \( x = \alpha V_\text{c} t + \frac{t - t_c}{2} \alpha (V_\text{c} + V_{\text{min}}) \)

where \( \alpha, \beta \) is the speed ratio of the quasi-meniscus to the sound shell along casting and width direction. \( g \) means gravitational acceleration. \( s \) is the oscillation stroke. \( t_c \) is the elapsed time of the rupture portion from the meniscus before decreasing speed.

Therefore, a necessary condition for recovery of rupture at the end of negative strip is following as

\[ \Psi(t_N, V_\text{c}, t) = F_{\text{c}}^* - (F_{\text{c}}^* - F_{\text{c}}^*) \geq 0 \].............(9)

Although Eqs. (1)–(9) according to Tsuneoka, 3) are derived using the geometry of the typical mold in the slab caster, the same equations are used for finding recovery conditions of tear shell in the thin slab caster. Because the additional lengths along casting and width direction due to funnel type mold in thin slab caster are almost negligible. (Both values are 0.5 mm and 1.67 mm, and the effective mold length is 900 mm). Also, \( n = 0.5 \) is generally used as power of Eq. (4) for prediction of shell thickness and the solidification constant \( m \) can be recalculated from the measured shell thickness at mold bottom in the normal conditions. When the normal casting speed is 4.5 mpm and the measured shell thickness at mold bottom in the normal condition is 12.7 mm, the value of \( m \) is 3.667. But, the thickness of initial shell near meniscus calculated from these values can be overestimated. Therefore, Tsuneoka 3) used that \( m = 1.475 \) and \( n = 0.66 \) for prediction of sticker breakout of the slab continuous casting.

To decide the solidification constants, a transient heat transfer model based on finite element method is used under the assumption that the heat transfer in the transverse and casting direction is negligible and the longitudinal heat flux profile for temperature field is a function of solidification time. Then, the thermal properties of the steel grade selected for process simulation and thermal boundary conditions are following as Table 1.

### Table 1. Thermal properties of the steel selected for process simulation and thermal boundary conditions.

<table>
<thead>
<tr>
<th>Temp. [°C]</th>
<th>Conductivity [W/mm°C]</th>
<th>Capacitance [J/mm°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>0.03182</td>
<td>0.00867</td>
</tr>
<tr>
<td>900</td>
<td>0.02680</td>
<td>0.00492</td>
</tr>
<tr>
<td>1100</td>
<td>0.02847</td>
<td>0.00495</td>
</tr>
<tr>
<td>1300</td>
<td>0.03009</td>
<td>0.00493</td>
</tr>
<tr>
<td>1500</td>
<td>0.03163</td>
<td>0.004915</td>
</tr>
</tbody>
</table>

* Thermal properties for 0.04% Carbon steel
- liquidus temperature: \( T_{\text{liq}} = 1528°C \)
- solidus temperature: \( T_{\text{sol}} = 1518°C \)
- latent heat = 270 kJ/kg, density = 7280 kg/m³

* Thermal boundary conditions
- superheat temperature: \( \Delta T = 30°C \)
- casting speed: \( V_\text{c} = 4.5\text{mpm} \)
- heat flux profile:

\[ q(\text{W/m}²) = 0.75q_0 \] where \( q_0 = 5.403 - 0.99\sqrt{t(\text{sec})} \)

![Figure 8](image)

**Fig. 8.** Thickness profile of solidified shell growing along the center of the broad face funnel mold.

3.3. Recovery Conditions of Sticking Type Breakout

In the current investigation, the following assumptions are used to find the recovery conditions such as minimum casting speed, decreasing speed gradient from normal to the replaced value, holding time of minimum casting speed and increasing speed gradient from minimum to normal speed.  
1) The thickness of repaired shell at mold bottom is larger than that of sound shell.  
2) The torn shell is repaired before the position of the thermocouple to check the recovery.  
3) The increasing time of casting speed after holding of replaced casting speed exists before the repaired shell is extracted at the mold.

When existence of quasi-meniscus is predicted from the peak temperature pattern indicating that a rupture shell moves downwards the mold bottom, alarm signal is on, and casting speed is immediately decreased to allow the additional solidification of the shell in the mold. **Figure 9** shows a schematic diagram of recovery conditions after the occurrence of a quasi-meniscus.

The mechanism to find recovery limits of the rupture portion are described below.

From the assumptions 1) and 3), the solidification of the quasi-meniscus can be allowed during the sum of the holding and increasing time and the repaired shell thickness at mold bottom is larger than that of normal condition.
The position at the end of negative strip, the quasi-meniscus at the position increasing speed during decreasing speed, holding the minimum speed and holding time is \( \Delta t_r \), \( t^- \) and ‘nor’ mean ‘repairing’ and ‘normal’. Also, a \( F_r \) and \( F_{nor} \) mean \( r \) and ‘nor’ mean ‘repairing’ and ‘normal’. Also, a flow, \( \Delta \Delta \Delta \), \( \Delta \), \( \Delta \), \( \Delta \), \( \Delta \), \( \Delta \). From the assumption 2), a torn shell is repaired before the position \( L_d \) of the thermocouple to check the recovery.

\[
\Delta L_r = \Delta L_h + \Delta L_c > L_m - L_d \quad \text{.............(14)}
\]

\[
L_c + \Delta L_{dec} < L_d \quad \text{where} \quad L_c(t=t_c) = L_{TC1} + \alpha V_c \Delta t_{alarm} \quad \text{.............(15)}
\]

\[
\Delta L_{dec} = \alpha L_c \frac{\partial V}{\partial t}_{dec} (t - t_c) + V_c \quad \text{.............(16)}
\]

\[
\Delta L_h = V_{min} \Delta t_h \quad \text{.............(17)}
\]

\[
\Delta L_i = \frac{\partial L_{dec} + \Delta L_c + \Delta L_i}{\partial t} \left( t - t_c - \Delta t_{dec} - \Delta t_h \right) + V_{min} \quad \text{.............(18)}
\]

where \( \Delta L_{dec} \), \( \Delta L_c \) and \( \Delta L_h \) mean the length passed by shell during decreasing speed, holding the minimum speed and increasing speed. \( \Delta t_{alarm} \) is the elapsed time from detecting the quasi-meniscus at the position \( L_{TC1} \) of \#1 thermocouple to starting of decreasing speed and \( L_c \) is the starting position of decreasing speed with the gradient of \( (\partial V/\partial t)_{dec} \).

Also, from the necessary condition for recovery of rupture at the end of negative strip, \( \Psi(t_c, V_c, t) = F_s - (F_s - F_{nor}) = 0 \), the minimum speed can be controlled as follows.

\[
V_{min} < \frac{V^*}{V_{min}} (\Psi_{L_c=L_d} = 0) \quad \text{.............(19)}
\]

Finally, the recovery limits are following,

- **Recovery time**
  \[
  \Delta t_r^{lim1} = \Delta t_r < \Delta t_r^{lim2} \quad \text{with} \quad \Delta t_r^{lim1} = \frac{L_m}{V_c}, \quad \Delta t_r^{lim2} = \frac{L_m - L_d}{V_{min}} \quad \text{.............(20)}
  \]

- **Gradient of decreasing speed**
  \[
  \frac{\partial V}{\partial t}_{dec} \leq \frac{\alpha (V_c^2 - V_{min}^2)}{2(L_m - L_c)} \quad \text{.............(22)}
  \]

- **Holding time of minimum speed**
  \[
  \Delta t_h < \Delta t_h^{lim} = \frac{2}{(\partial V/\partial t_i)_{dec}} (L_m - L_d - V_{min} \Delta t_i) \quad \text{.............(23)}
  \]

- **Increasing time of speed with \( (\partial V/\partial t)_{i} \)**
  \[
  \Delta t_i > \Delta t_i^{lim} = \frac{2}{(\partial V/\partial t_{i})_{dec}} (L_m - L_d - V_{min} \Delta t_i) \quad \text{.............(24)}
  \]

For finding admissible process conditions satisfying the limit conditions for repairing the sticking type breakouts, the effects of process parameters such as casting speed \( V_c \), minimum speed \( V_{min} \), holding time \( \Delta t_h \) and the gradients \((\partial V/\partial t)_{dec} \), \((\partial V/\partial t_{i})_{dec} \) of decreasing and increasing speed are investigated with using the conditions listed in Table 2.

**Figure 10** shows an example for recovery state of rupture shell. As the frictional force acting on the shell at the end of the negative strip period decreases, the shear strength increases during decreasing speed region. When the speed is \( V^* \), the sum of forces acting on the shell is...
equal to zero. After that time, the repairing of torn shell during decreasing speed is immediately allowed as decreasing casting speed is lower than required speed for rupture recovery of shell, and the molten steel is continuously solidified during the time interval $D_f^\ast \Delta t^\ast_{\text{dec}}$ and $D_f^\ast \Delta t^\ast_{\text{r}}$.

Table 3 shows the effect of process parameters on the solidification time and shell thickness during repairing the sticking type breakouts, i.e. the thickness ratio $d_{\text{r}}/d_{\text{nor}}$ of repaired solidified shell to normal shell increases with the increase of casting speed and holding time of minimum speed, but decreases with the increase of minimum speed, gradient of decreasing speed and gradient of increasing speed.

Also, the time interval ratio $\Delta t_i/\Delta t_h$ decreases with the increase of casting speed, gradient of decreasing speed, holding time of minimum speed, minimum speed and gradient of increasing speed.

Among all admissible conditions of Table 2, the minimum speed can be determined by considering the safety at repairing measurement position of rupture shell, as may be seen from Fig. 11.

Figure 12 shows a determined speed pattern for breakout prevention when the necessary condition values at the position of rupture measure is 0.19.

4. Controls for Breakout Prevention

The automation for Breakout detection and healing sequences are following: 1) the BOPS checks the Breakout symptom in advance and send alarm signal to the casting speed controller; 2) Then the speed controller decreases the speed from the pre-defined pattern, holds during a fixed time and re-increases the speed again to the normal casting
value; 3) In this case, the mold level controller and the secondary cooling controller is responsible for the minimum mold level variation and the proper cooling, respectively, for given operation changes.

Given the proposed speed pattern, the mold level control should have ability to compensate the mass-flow change as fast as possible to prevent the overflow or the big change of the molten steel.

The field tests only with PID control are mostly ended with molten steel overflow because PID control only considers the level error and the detuned controller cannot quickly cut the inflow into the mold from tundish. This nullifies the effects of BOPS and causes the decrease of production amount and the damage of the plant.

Therefore, this section proposes a noble mold level control method to guarantee the stable healing sequences irrespective of abrupt speed changes.

For this, the controller is designed to have three major functions as shown in Fig. 13. One is the adoption of the feed-forward function which is capable of controlling the inflow by using the actual speed change, where the compensations is calculated based on the stopper geometry and given outflow as follows,

$$
\Delta h_f = \frac{\Delta v_c \cdot T \cdot W}{k \cdot \sqrt{2 \cdot g \cdot H_{\text{tund}}}} \tag{25}
$$

where $k$ is stopper coefficient, $\Delta h_f$ is the stopper position change by feed-forward term, $g$ is the gravitational acceleration, $H_{\text{tund}}$ is the height of molten steel in the tundish, $\Delta v_c$ is the speed change, $T$ is the slab thickness, $W$ is the slab width.

The second is the use of fuzzy logic based controller as a main feedback control. The various control logics such as PID, $H_{\text{tund}}$, fuzzy logic can be used for this purpose. In the POSCO’s thin slab caster, the fuzzy logic controller is adopted as main controller due to its flexibility to deal with various situation and operator’s experiences.

$$
\Delta u_f = k_1 \cdot e + k_2 \cdot \int \Delta u_c \, dt \tag{26}
$$

where $h_f$ is the output of fuzzy logic based controller which contains a fuzzy control term $\Delta u_f$ and a proportional term. $k_1$ and $k_2$ is the gains of the proportional and fuzzy term, respectively. And $e$ is error between $y_{\text{ref}}$ and level sensor.

The last is the gain-scheduling functions according to the changes of operating conditions. The upper part of Fig. 14 shows the nonlinear inflow characteristics according to the stopper opening, and the lower part shows the gradient of the inflow. This gradient feature informs that the inflow variations to the stopper opening are increasing as casting speed is decreasing. Previously mentioned speed changes cause the big changes of operating conditions because the speed variations are ranging from nearly maximum to mini-

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**Fig. 11.** Effect of minimum casting speed on the $\Psi(t_d)$.

**Fig. 12.** A speed pattern for breakout prevention.

**Fig. 13.** Proposed controller architecture.

**Fig. 14.** Input flow according to the stopper opening.
mum. Thus, the controller itself needs to be retuned on each operating point. In real situation, a fixed gain is not good enough for minimizing the mold level variation in whole control ranges. In order to overcome this, a gain scheduling method is introduced for the fuzzy logic controller, where the fixed gains, $k_1$ and $k_2$ are changed to the time-varying form.

For the determination of the initial parameter values, a software simulator is designed based on the mass-balance equation and electro/mechanical information. And the fine tuning is performed during the on-line testing.

During the repairing time, if the cooling pattern of secondary cooling zone is maintained to the same condition of normal casting, the rolling force at roughing mill area increases too much due to the overcooling at very low speed. In that case, the motor current goes to its limit value and the drives trips automatically to protect the motor and electric circuits. In order to prevent this kind of phenomenon, the over-cooled point is tracked and the cooling pattern is adjusted to soft-cooling in secondary cooling zone as shown in the Fig. 15.

5. Application Results

The proposed logics are implemented into the control system and the field tests are performed to check the effectiveness of the proposed method for the healing of rupture point and smooth restarting of the casting sequences. The system configuration and healing procedures are shown in Fig. 16, where round number indicates the previously mentioned healing sequences.

Figure 17 shows a test result when overall algorithms are applied, where the mold level is the dark color (black) whereas the speed is the light color (red). The BOPS alarm is generated around 15590 s and speed is decelerating. With the existing PID controller, the molten steel overflows very often and moves with very big variations. This makes the casting procedure stop. Thus, the healing method could not be applied. By using the proposed method, since the variations of mold level are dramatically reduced and stably controlled, castings for profitable materials are possible.

Figure 18 is a real result for repairing sticker breakout when a casting speed is 4.5 m/min, $(\partial V/\partial t)|_{\text{dec}} = -1$ m/min/s and $V_{\text{min}} = 0.5$ m/min. In the figure, (A) part shows small rupture signs between the upper and lower ruptured shells at which ruptured shell was just solidified by decreasing speed. Then, it is recovered immediately although it occurs. Also, in (B) parts as quasi-meniscus, the hot tear marks was occurred when shell rupture was repeated.

With this technology, the automatic restarting rate is increased from 0 to 92% and this makes it possible to cast the hard-casting materials such as medium-carbon steel, Erosion–Proof Steel, High Carbon Steel, etc. The anticipated profit will be 6.14 million dollars per year from the decrease of casting suspension, the productions of high-val-
ued steel, etc.

Now, the proposed system is working on-line in two thin slab caster in POSCO and will be applied to various casting machines.

6. Concluding Remarks

This paper described a recovering technology from the sticking type breakout, where the derivation of healing conditions, the improvements of mold level control logic, and cooling rates modification are explained.

By applying the proposed method in the actual plant, the automatic restarting rate is increased from 0 to 92% and this makes it possible to cast the hard-casting materials such as medium-carbon steel, Erosion–Proof Steel, High Carbon Steel, etc. The anticipated profit will be 6.14 million dollars per year from the decrease of casting suspension, the productions of high-valued steel, etc. Moreover, the high speed casting is highly required in the conventional caster to increase the production rate. For this the proposed method can be easily replicated with a least modification.

For the next research topics, the upgrading of breakout Prediction algorithm for general cases, the generalization of healing condition derivation, the studying of adaptive capability for mold level controller will be handled.

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