Analysis of Mold Level Hunching by Unsteady Bulging during Thin Slab Casting

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(Received on April 8, 2002; accepted in final form on June 17, 2002)

In order to analyze the phenomenon of mold level hunching (MLH) during thin slab casting process, the variation of the mold level and the bulging of strand were measured and analyzed using Fast Fourier Transform (FFT) spectrum analysis. Both of mold level hunching and bulging had the same frequency and the specific frequency corresponded to the main roll pitch of the thin slab caster. The unsteady bulging was found to be a main reason of mold level hunching. The unsteady bulging profile through the full range of the caster and the height of mold level hunching were calculated using a heat transfer model and a continuous beam model. The effects of process variables on mold level hunching and the process condition of reducing mold level hunching were studied. The amount of mold level hunching increased as unsteady bulging increased due to the hunching of casting speed. An aperiodic roll pitch between segments could be effective in reducing mold level hunching.

KEY WORDS: mold level hunching (MLH); unsteady bulging; FFT analysis; continuous beam model; thin slab casting; aperiodic roll pitch.

1. Introduction

The recent technologies of continuous casting process are being developed toward the near-net-shape casting process1–2) where the cast steels are closer to the final product size and the typical commercialized technology is the thin slab casting process.1–4) The strand thickness of thin slab casting is in the range of 50–100 mm while that of the conventional casting process is 200–300 mm, subsequently the casting speed of thin slab casting is about three times higher than that in the conventional casting process to have the same productivity. This high casting speed leads to several operational problems which were not reported at the conventional casting process. The typical operation problem during thin slab casting is the fluctuation of mold level (mold level hunching or mold level fluctuation: MLH).

It is known that the MLH causes strand surface cracks, disturbance of melting and inflow of mold flux and even breakout in severe cases. This MLH is a main obstacle in increasing the casting speed. Many factors such as inaccuracy of mold level sensor, disturbance of liquid steel flow inside the mold and volume change of liquid steel in the mold could cause the MLH. The effects of mold level control systems5–7) and the flow of liquid steel in the mold8–10) on MLH have been studied for many years, and many solutions have been found out in order to reduce their influence on MLH.

The flow behavior of liquid steel in the mold can be subdivided into three kinds such as inflow of liquid steel from tundish, outflow due to downward movement of strand with casting speed and liquid steel flow inside the solidified shell. The volume of liquid steel inside the solidified shell can be changed by strand bulging at the secondary cooling zone. The fluctuation of bulging profile with time, called the unsteady bulging leading to MLH, causes the volume change of liquid steel with time.

The importance of unsteady bulging and the induced MLH has been recently highlighted with the development of high speed thin slab casting process.11–21) However, their origin and detailed mechanisms have not been known clearly until now. The numerical analysis of strand bulging considering movement of strand and unsteady behavior through the full range of a continuous caster has not been reported.

The purpose of this study is to analyze MLH and unsteady bulging, using a spectral analysis of the measured and the calculated data of unsteady bulging profile, and to establish the proper process window of reducing MLH. The measured data of mold level, casting speed and bulging at the commercial thin slab caster were analyzed using a spectral analysis to investigate the relationship between MLH and unsteady bulging. The unsteady bulging profile through the full range of the thin slab caster and induced MLH were calculated using a heat transfer model and a continuous beam model. The effects of process variables on MLH and the process condition of reducing MLH were studied.
2. Unsteady Bulging and MLH

During the continuous casting process of a slab, the bulging deformation of strand occurs by the ferrostatic pressure of liquid steel acting on the solidified shell between the two supporting rolls. The bulging of strand can be divided into static and dynamic bulgings according to the movement of strand, and steady and unsteady bulging according to the variation with time. Figure 1 shows the schematic illustration of static, dynamic, steady and unsteady bulgings. In static bulging, the position of the maximum bulging is the center of the roll pitch and the symmetric bulging profile can be expected. In dynamic bulging, the position of the maximum bulging moves from the center of the roll pitch to downstream by a creep deformation and the movement of strand. If the bulging profile is not varied with time, bulging is steady even in dynamic case. In case of unsteady bulging, the bulging profile is not steady but varied with time.

The bulging displacement can be expressed as follows.

\[ d = f(v, P, L, S, T, t) \] ........................................(1)

where \( d \) is the bulging displacement, \( v \) is casting speed, \( P \) is ferrostatic pressure, \( L \) is roll pitch, \( S \) is shell thickness, \( T \) is strand temperature, and \( t \) is time, respectively. Bulging is steady when the variables of Eq. (1) are constant with time. In real process conditions, the bulging variables except the roll pitch hardly remain constant with time. Unsteady bulging can occur due to the variation of the bulging variables with time, and the periodic unsteady bulging is observed when MLH occurs periodically.

From Eq. (1), the causes for unsteady bulging can be regarded as the variation of casting speed, ferrostatic pressure and strand temperature (shell thickness). It was reported that the period of the variation of casting speed is the same as that of bulging and MLH when MLH is mainly generated by unsteady bulging. The variation of ferrostatic pressure can be induced by the change of mold level, and the variation of strand temperature can be caused by the variation of liquid steel temperature in ladle and tundish, the variation of heat flux in the mold due to MLH, and inhomogeneous solidification.

MLH can be generated and the height of MLH increases by unsteady bulging, that is, MLH is amplified at the same period (hunching period). Figure 2 shows the schematic illustration of MLH mechanism by unsteady bulging. In case of steady bulging, the mold level remains constant because the volume of liquid steel inside the solidified shell does not change. In case of unsteady bulging, when the convex part of the solidified shell locates between rolls, the volume of liquid steel increases and the mold level falls. When the concave part of the solidified shell locates between rolls, the mold level rises. When the period of mold level variation is equal to that of unsteady bulging, MLH and unsteady bulging can be amplified with each other at certain conditions such as specific casting speed at the given roll geometry.

3. Experimental Procedures

Figure 3 shows roll profile of the thin slab caster. The caster has the parallel funnel mold with the thickness of 75 mm and the total 6 roll segments from 0 to 5. The strand is reduced to 60 mm thickness at segment 0, called the liquid core reduction (LCR), and the optimum casting speed is designed to be 5.0 m/min. The roll pitches at each segment are also listed in Fig. 3. It is notable that the roll pitches from segment 1 to segment 4 are the same as 195 mm.
where $T=T(x,z)$ is the temperature of strand at thickness direction $x$ and casting direction $z$, $k=k(T)$ is thermal conductivity, $\rho$ is density, and $H$ is enthalpy. The enthalpy $H$ is defined as the sum of sensible and latent heats.

$$H(T) = \int_0^T \left( c(\tau) - L \frac{\partial f_s(\tau)}{\partial \tau} \right) d\tau \quad \text{(3)}$$

where $c$ is the specific heat, $L$ is latent heat and $f_s=f_s(T)$ is solid fraction. The initial and boundary conditions are as follows.

$$T = T_0, \quad -k_n \frac{\partial T}{\partial n} = q_s \quad \text{(4)}$$

$$q_s = h(T-T_w) \quad \text{(5)}$$

where $T_0$ is the initial casting temperature of liquid steel, $n$ is direction normal to strand surface, $q_s$ is heat flux on the surface, $h$ is heat transfer coefficient, $T_w$ is temperature of cooling water.

The heat transfer coefficient for the mold region can be given as follows.

$$h = a(1-bz) \cdot \bar{q} \quad \text{(6)}$$

where $z$ is the distance below the meniscus of mold, $\bar{q}$ is average heat flux, which is the function of the mold width, mold water flux and tundish superheat, $a=1.35\times10^{-3}$ and $b=0.8$. For the secondary cooling zone, the heat transfer coefficient can be described as follows.

$$h = aW^b + c \quad \text{(7)}$$

where $W$ is the spray water flux. The parameters of Eq. (7) were determined to give optimum agreement to measured surface temperatures for the various conditions of casting speed and spray water flux.

### 4.2. Strand Bulging Calculation (Continuous Beam Model)

In order to calculate the amount of MLH due to unsteady bulging, the dynamic and unsteady bulging profiles through the full roll pitches from mold exit to metallurgical length is required. In this study, the continuous beam model proposed by Yoshii et al.\textsuperscript{15} has been used to calculate the dynamic and unsteady bulging profile of strand through the full roll pitches. The two-dimensional bulging model of the longitudinal cross section through the middle of the strand shown in Fig. 5(a) can be modeled by the continuous beam model with multi-roll pitches shown in Fig. 5(b). In the continuous beam model, the displacement $w$, slope $\theta$, moment $M$ and shear force $F$ at $n$th roll can be calculated by solving simultaneous equations constructed using continuity and equilibrium conditions. The main features of this model are that the micro-distribution of creep strain in the shell thickness direction, which is difficult to consider in the simple beam modeling, is transformed into the shell curvature as a macro-quantity and the movement of strand can be modeled by the step-by-step mesh shifting of creep strain.
4.3. Material Deformation Behavior

The strand deformation from bulging depends largely on the high temperature creep. The creep behavior of strand can be regarded as primary creep because the strain range is small enough and the cycle time of stress alternation with the movement of strand is also short. The elasto-viscoplastic constitutive equation proposed by Kozlowski et al. was used in this study and the strain rate is described by the following equation.

\[
\dot{\varepsilon} = C \exp\left(\frac{-Q}{T + 273}\right) \sigma^{m-n} \quad \ldots (8)
\]

where
\[
C = 0.3091 + 0.2090 \text{(wt\%C)} + 0.1773 \text{(wt\%C)}^2 \quad Q = 17160
\]
\[
m = 6.365 - 4.521 \times 10^{-3}(T+273) + 1.439 \times 10^{-4}(T+273)^2
\]
\[
n = -1.362 + 5.761 \times 10^{-4}(T+273) + 1.982 \times 10^{-5}(T+273)^2
\]

The Eq. (8) is the form of the time-hardening law and was transformed into that of the strain-hardening law in order to express the strain rate in the shell subjected to alternating stresses.

\[
\dot{\varepsilon}_n = (n+1)^{m+n+1} C^{(n+1)} \sigma^{m-n} \quad \ldots (9)
\]

The elastic behavior of strand was modeled using temperature dependent Young’s modulus from Mizukami et al.27

4.4. Procedure of Numerical Calculations

The analysis conditions for the thin slab caster is given in Table 1 and the composition of steel used in this study is given in Table 2.

For the procedure of numerical calculations, at first, the heat transfer model based on FDM has been used to calculate shell thickness and strand temperature at mold and secondary cooling zones. Next, the unsteady bulging profile through the full roll pitches from mold exit to metallurgical length has been calculated in a longitudinal cross section through the middle of the strand using the continuous beam model. For the modeling of unsteady bulging numerically, the fluctuation of bulging variables like casting speed, ferrostatic pressure and strand temperature must be applied. It was shown that unsteady bulging could be related with the periodical variation of casting speed, ferrostatic pressure and strand temperature19) and the method of the variation of casting speed was used in this study.

Figure 6 shows the schematic diagram of evaluation of MLH amount by unsteady bulging.

5. Results and Discussions

5.1. Analysis of Experimental Data of MLH

Figure 7 shows the variation of MLH and casting speed and their FFT analysis. This type of MLH is the typical
type of amplifying MLH. MLH, which begins to be amplified at casting speed of 3.9 m/min, continues for 1–2 min even after casting speed is reduced, and it decreases as casting speed is lowered as 3.2 m/min. In order to examine the relation between MLH and casting speed, the FFT analysis has been conducted dividing the time range into three regions with the variation of casting speed. The results of the FFT analysis of mold level are shown in the right side of Fig. 7. The peak frequencies of 0.31 Hz in region A, 0.283 Hz in region B, and 0.254 Hz in region C were observed and all these peak frequencies were observed in region A+B+C. As the casting speed decreases, the peak frequency of MLH also decreases. When casting speed is divided by the characteristic frequency, or multiplied by the period, the following equation can be obtained.

\[ V_c \cdot T_f = P_H \] ...........................(10)

where \( V_c \) is casting speed (mm/s) and \( T_f \) is the period of MLH (s). \( P_H \) is about 200 mm and corresponds to the roll pitch of segment 1–4 of 195 mm. This constant can be

Fig. 7. Variation of MLH and casting speed and their FFT analysis.

Fig. 8. Variation of MLH, casting speed and bulging and their FFT analysis.
called “hunching pitch”.

The left side of Fig. 8 shows the variation of mold level, casting speed and bulging between segment 2 and 3 and the right side shows their FFT analysis. The magnitude of bulging in Fig. 8 is a relative value indicating the distance between steel plate and gap sensor fixed to the segment cover. The magnitude of bulging is not nearly changed below casting speed of 3.9 m/min, and the magnitude of MLH is about ±5 mm at the casting speed of 3.9 m/min. But bulging increased above the casting speed of 3.9 m/min, and also MLH increases. The results of the FFT analysis in the region of high casting speed (t=10 650–10 830 s) are shown in the right side of Fig. 8. The main peak frequencies of the spectrum of mold level are 0.361 and 0.147 Hz, and weak intensity of spectrum is 0.44 Hz. The 0.361 Hz and 0.44 Hz frequencies correspond to the roll pitch of segment 1–4 and segment 0, respectively, and 0.147 Hz to the rotation of pinch rolls. The peak frequencies of 0.361 Hz and 0.142 Hz are also observed in the spectrum of casting speed and it is shown that the intensity of the spectrum is lower than that of mold level. The characteristic frequencies of the spectrum of bulging are 0.147 Hz, 0.361 Hz and 0.44 Hz. The 0.361 Hz frequency corresponds to the roll pitch of segment 1–4 and the 0.44 Hz frequency to the roll pitch of segment 0. Because measured position of bulging is between segment 1 and segment 2, unsteady bulging of segment 0, which corresponds to 0.44 Hz, is dominant role to the spectrum of bulging. But in the spectrum of MLH, the 0.44 Hz is very weak, because the mold level is affected by the all unsteady bulging of strand, and the number of the roll pitches of 160 mm (segment 0) is less than that of the roll pitch of 195 mm (segment 1–4).

From Fig. 8, it can be seen that unsteady bulging, casting speed and MLH have strong relationship. Figure 9 shows the relationship between MLH and bulging with time and it is known that the mold level rises as bulging decreases and falls as bulging increases. This result is in good agreement with the mechanism of MLH by unsteady bulging as shown in Fig. 2. In case of the increased bulging, the volume of liquid steel inside the solidified shell under the mold increases, and, as a result, mold level goes down and vice versa.

From the results mentioned above, MLH at the thin slab caster is induced by unsteady bulging and MLH increases as the number of roll pitches of 195 mm within metallurgical length increases and can be amplified.

5.2. Heat Transfer Behavior of Strand

The variations of strand temperature and solidified shell thickness with distance from meniscus are shown in Figs. 10(a) and 10(b). The strand surface temperature is about 1200°C and the shell thickness is about 10 mm at mold exit. The metallurgical length is about 6.5 m. The solidification constant of the thin slab caster is known to be 22–24 (mm/min0.5) and the calculated metallurgical length is 5.5–6.5 m. Therefore, the temperature distribution of strand is thought to be reasonable and the following analysis of unsteady bulging and MLH has been conducted based on the calculated strand temperature.

5.3. Effects of Hunching of Casting Speed

Figures 11 and 12 show the profiles of steady and unsteady bulging, respectively. At constant casting speed, that is, steady bulging, the calculated bulging of about 1.5 mm occurs at the roll pitch 14 where the segment 1 starts and the roll pitch 22 where the segment 2 starts. The negative bulging occurs at the next roll pitches by the large bulging at the previous roll pitch. The negative bulging results from the movement of strand and creep deformation and the result of this analysis is in agreement with the result of
Matsumiya et al.\textsuperscript{22)}

With the hunching of casting speed, unsteady bulging occurs. The straight line in Fig. 12 corresponds to the bulging profile at 5\% hunching of casting speed when bulging is maximum, that is, the mold level is at the bottom position and the dashed line corresponds to the profile when the mold level is at the top position. The amount of MLH is decided by the area between the straight line and the dashed line.

Figure 13 shows the calculated variations of the amplitude of MLH with time at steady bulging from the conditions as shown in Fig. 11. In case of steady bulging, the mold level is varied within the time of about 1 min showing the unsteady conditions of the early stage of casting, however, it reaches a steady condition after the time of 100 s when the strand starting at mold exit passes a metallurgical length. In case of unsteady bulging, the amplitude of MLH increase with time as shown in Fig. 14. The result of Fig. 14 was calculated applying the 5\% hunching of casting speed after reaching a steady condition (120 s). The amplitude of MLH due to unsteady bulging increases with time and the periodic MLH of about ±7 mm is shown after the time of 190 s. Because the amount of the hunching of casting speed is constant, MLH is no more amplified after the time of 190 s. The “self exciting mechanism,” where the bulging variables of casting speed and unsteady bulging interacts mutually, can be used in order to calculate the continuous amplification of MLH. Figure 15 shows the variation of amount of MLH with hunching of casting speed. As the hunching of casting speed increases, that is, unsteady bulging increases, the amount of MLH increases. Therefore, it is known that the amount of unsteady bulging is necessary to be minimized in order to reduce MLH.

5.4. Effects of Change of Roll Pitch

Examining the unsteady bulging profile of Fig. 12, the volume change of solidified shell is low at segment 0 where bulging is low and begins to increase at segment 1 where bulging is large and is amplified at segment 2 and 3, because the same roll pitches of segment 1–3 amplifies unsteady bulging downwards. The effects of the change of roll pitches (195 mm) at segment 1 on MLH has been analyzed.

Figure 16 shows the unsteady bulging profiles when the roll pitches of segment 1 are changed from 195 to 130 mm.
at 5% hunting of casting speed. In case of the roll pitch of 130 mm, the amount of bulging at segment 1 is considerably low and the increase of unsteady bulging at segment 2 and 3 is much lower than that of the roll pitch of 195 mm. This change of unsteady bulging leads to the change of the amount of MLH and the variation of amount of MLH with the change of roll pitch of segment 1 at 5% hunting of casting speed is shown in Fig. 17. While the amount of MLH is about 14 mm at the roll pitch of 195 mm at segment 1, the amount of MLH is largely reduced as about 1 mm at the roll pitch of 130 mm. The reasons that the amount of MLH is reduced considerably with change of roll pitch are that the absolute amount of bulging decreases with the reduction of roll pitches and the amplification of unsteady bulging is lowered by the different roll pitches. It is known that the change of roll pitch at segment 1 is very effective in reducing MLH.

5.5. Mechanism of MLH and Countermeasures

By the FFT analysis of MLH and bulging and the calculation of unsteady bulging, the mechanism of the generation and amplification of MLH can be estimated. According to the increase of casting speed, the thickness of solidified shell is reduced and the bulging of strand increases. Once the bulging profile deviating from the steady state is developed due to the factors such as the increase of bulging and the change of casting speed and passes an interval between rolls, the amount of bulging at the midpoint of roll pitch repeats increase and decrease with the period of roll pitch. That is, unsteady bulging with the period of roll pitch is developed. Once the unsteady bulging is developed, the volume change of liquid steel inside the solidified shell by unsteady bulging causes the movement of liquid steel. The liquid steel moves into the mold level direction because the solidification is completed into the crater end direction and in consequence the mold level is fluctuated with time concurrently.

When the unsteady bulging profile passes pinch rolls, the current of pinch rolls is varied due to the change of the working load on pinch rolls, thus casting speed is varied (hunching of casting speed). This is known from the fact that the same peak frequency was observed between casting speed and unsteady bulging as shown in Fig. 8.

Matsumiya et al.\(^\text{28}\) reported that the dynamic pressure of liquid steel was developed by the flow of liquid steel inside the solidified shell, that is, unsteady bulging. According to his analysis result in case of the same roll pitches, the internal pressure of liquid steel becomes maximum when the convex portion of the unsteady bulging profile arrives between rolls and it becomes minimum when the concave portion arrives between rolls. The dynamic pressure of liquid steel increases as casting speed and unsteady bulging increases.

When the mold level is varied by unsteady bulging, the position of the formation of initial solidified shell is varied and the thickness of the solidified shell is also varied. The variation of the thickness of the solidified shell which has same frequency with MLH increases unsteady bulging. The mechanism of MLH caused by unsteady bulging was shown in Fig. 18.

The amplification of MLH has a close relationship with the roll pitch configuration. If the rolls are arranged with the successive same roll pitches, unsteady bulging grows passing the rolls with the period of the roll pitch and in consequence MLH becomes amplified with the same period. At this case, casting speed, dynamic pressure and the thickness of the solidified shell becomes varied with the same period as shown in Fig. 18, so the amplification of MLH becomes accelerated.

In order to reduce MLH by unsteady bulging in the continuous casting process, the methods such as the strong cooling at the secondary cooling zone, which reduces the amount of bulging, and the change of roll pitch configuration (reduction or irregular arrangement of roll pitches), which makes the period of unsteady bulging irregular, are effective. Actually it was possible to reduce MLH by un-
steady bulging by means of the hard cooling at secondary cooling zone and the change of roll pitch configuration in a field operation.  

6. Conclusions

The variation of the mold level and the bulging of strand were measured in the commercial thin slab caster and analyzed using FFT analysis. The unsteady bulging profile and the induced MLH were calculated using a heat transfer model and a continuous beam model. FFT analysis showed the same hunching period among MLH, bulging and casting speed. This hunching period corresponded to the main roll pitch of the thin slab caster. MLH was induced by unsteady bulging at secondary cooling zone and increased as the number of the same roll pitch within metallurgical length increased. The amount of MLH increased as unsteady bulging due to the hunching of casting speed increases and it is effective to make the roll pitches different between segments in reducing MLH. The mechanism of MLH caused by unsteady bulging was proposed based on FFT analysis of measured data and calculation of unsteady bulging.

Acknowledgments

Authors wish to thank A. Yoshii, FPS Group, Sumitomo Heavy Industries, Ltd., Japan for helpful discussions.

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