Generation Mechanism of Unsteady Bulging in Continuous Casting-1

-Development of Method for Measurement of Unsteady Bulging in Continuous Casting-

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In the continuous casting of steel, mold level fluctuation caused by unsteady bulging of the solidifying shell affects the surface quality of the product and stable operation of the continuous casting process. To clarify this problem, inter-roll bulging and unsteady bulging in experimental casting machines and commercial continuous casting machines have been measured by various methods in a number of studies. In this study, the fluctuation of inter-roll bulging with time in a commercial continuous casting machine was measured by an ultrasonic range finder using a water column. In these measurements, the fluctuation of the segment was also considered. The validity of the measured data was estimated by comparison with the mold level. The results showed that both inter-roll bulging and the mold level fluctuated with the cycle calculated from the roll pitch and casting speed, and the amplitude of the mold level fluctuation converted from the amount of fluctuation of inter-roll bulging corresponded to the actual mold level fluctuation. Therefore, the cycle and absolute amount of inter-roll bulging fluctuation measured in this study were considered reasonable. These results also revealed that the value measured in this study corresponded directly to the fluctuation of inter-roll bulging as such.

KEY WORDS: continuous casting; unsteady bulging; mold level fluctuation.

1. Introduction

In the continuous casting of steel, the phenomenon in which the solidified shell bulges due to the ferrostatic pressure of the molten steel as the slab passes through the series of rolls in the continuous casting machine is called inter-roll bulging. As inter-roll bulging is caused by elasto-plastic deformation, the bulging of the solidified shell which occurs between the rolls does not completely return to its original shape when the slab moves to the next roll. This means the slab has a bulging shape as it moves through the caster. Because the volume of molten steel in the slab changes at each roll, the mold level fluctuates at the roll pitch cycle. This phenomenon is called mold level fluctuation caused by unsteady bulging, and affects the surface quality of the product and stable operation of the continuous casting process.

Various approaches such as increasing the amount of secondary cooling water¹⁾ and adoption of a non-cyclic roll pitch²⁾ have been taken to suppress unsteady bulging.

Inter-roll bulging and unsteady bulging have been measured in a number of studies. Saeiki *et al.*³⁾ measured the

amount of inter-roll bulging in a commercial continuous casting machine by using a position detector in order to investigate the effectiveness of short-pitch divided rolls for suppression of inter-roll bulging. Maeno *et al.*⁴⁾ measured the amount of inter-roll bulging just below the mold in an experimental casting machine from the displacement of a measuring rod pressed into the slab in order to clarify the factors affecting the amount of inter-roll bulging. Kataoka *et al.*⁵⁾ measured the amount of bulging below the pinch rolls by contact and non-contact methods. Fujii *et al.*⁶⁾ conducted bulging simulation tests by using plasticine and measured the amount of bulging with a differential transformer in order to investigate the relationship between the pressure and the amount of bulging. Kanazawa *et al.*⁷⁾ measured the bulging profile between the rolls in an experimental casting machine by using a contact linear transducer. Ishimura *et al.*⁸⁾ measured the deformation behavior of the slab and the rolls by installing a differential transformer in the segment frame of a commercial continuous casting machine and investigated inter-roll bulging behavior. Nakamori *et al.*⁹⁾ measured the amount of inter-roll bulging in a commercial continuous casting machine with a contact position detector. Lee *et al.*¹⁰⁾ measured the movement of the driven rolls in a commercial continuous casting machine with a displace-

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ment transducer and investigated unsteady bulging behavior. Yoon *et al.*¹¹⁾ measured the unsteady bulging behavior in a commercial thin slab casting machine by measuring the displacement of a guide rod in contact with slabs.

As outlined above, many studies have measured inter-roll bulging and unsteady bulging in experimental casting machines and commercial continuous casting machines.

However, there have been few studies in which unsteady bulging in a commercial continuous casting machine was measured in consideration of segment fluctuation, and the validity of the measured data was examined by comparison with the mold level.

In this study, the fluctuation of inter-roll bulging with time (*i.e.*, unsteady bulging) in a commercial continuous casting machine was measured in consideration of the fluctuation of the relative distance from the segment to the ground. Furthermore, the validity of the measured unsteady bulging data was estimated by comparison with the cycle and volume change of the mold level.

2. Experimental Method

An ultrasonic range finder using a water column was installed in a commercial vertical bending continuous casting machine, and the amount of fluctuation of inter-roll bulging during casting was measured intermittently. The ultrasonic range finder was installed between segments about 4 m upstream from the predicted crater-end position. **Figure 1** shows a schematic diagram of the ultrasonic range finder installed in the commercial continuous casting machine. In this measuring system, an ultrasonic wave was applied to a slab using the water column, and the relative distance between the ultrasonic range finder and the slab was measured from the propagation time and sonic velocity. The resolution of this measuring system was 0.01 mm, and the measurement accuracy of the relative distance was below 0.05 mm.

As the ultrasonic range finder was fastened to the segment, it was considered possible that a value which included segment fluctuation was measured as the fluctuation of inter-roll bulging when the segment fluctuated greatly during measurement of inter-roll bulging. In order to measure the fluctuation of the segment in which the ultrasonic range finder was installed, a laser range finder was installed on the ground facing the segment.

In addition, in order to investigate the amount of fluctuation of the roll gap in the segment when a slab with a

bulging shape passed through the rolls, the fluctuation of the distance from the ground at the segment around the crater-end position was also measured by a laser range finder. It is difficult to measure roll gap fluctuations directly due to restrictions of the equipment. However, since the lower segment was fixed on the ground, it was considered possible to measure the value equal to the amount of roll gap fluctuation by measuring the fluctuation of the upper segment. Here, deformation of the frame, bearing and so on was ignored.

The crater-end position was converted from the ultrasonic waveform obtained by application of the ultrasonic wave to the slab during casting.

Unsteady parts such as the initial stage of casting were avoided, and the part with a regular casting velocity from the mold to the crater-end position was measured.

The moving average value of the measured data within a certain time was calculated as a reference position (=0 mm) at each measurement time, and the difference from the reference position was calculated as the amount of fluctuation.

3. Experimental Results

3.1. Temporal Change and Cycle in Inter-roll Bulging and Mold Level

First, as planned, the crater-end position converted from the ultrasonic waveform was about 4 m downstream from the position where the ultrasonic range finder installed.

Figure 2 shows an example of the fluctuation of inter-roll bulging measured by the ultrasonic range finder. The measurement period shown in Fig. 2 was judged to be a steady part, and the slab was cast at the regular casting velocity from the mold to the crater-end position in this part.

Figure 3 shows the fluctuation of the segment in which the ultrasonic range finder was installed at the same time as that in Fig. 2. As shown in Figs. 2 and 3, the amount of fluctuation of the segment in which the ultrasonic range finder was installed was much smaller than the amount of fluctuation of inter-roll bulging. These results revealed that the value measured by the ultrasonic range finder using the water column contained almost no fluctuation of the segment, and the measured value was the fluctuation of inter-roll bulging as such, and was not significantly affected by any other factors.

Due to restrictions on the installation accuracy of the ultrasonic range finder in regard to the vertical axis in Fig. 2, 0 mm could not be matched with the pass line between

Fig. 1. Schematic diagram of equipment for measurement of inter-roll bulging.

Fig. 2. Fluctuation of inter-roll bulging.

Fig. 3. Fluctuation of relative distance from segment to ground.

Fig. 4. Mold level fluctuation during measurement of unsteady bulging.

the rolls. For this reason, it was not possible to measure the absolute amount of the inter-roll bulging. However, quantitatively measurement of the difference between the maximum and minimum amounts of inter-roll bulging (that is, the absolute amount of fluctuation) was possible by this experimental method.

Figure 4 shows the mold level fluctuation at the same time as that in Fig. 2. Figure 5 is an enlarged figure of the horizontal axis in Figs. 2 and 4. As shown in Fig. 4, both fluctuated with the same cycle.

As also shown in Figs. 2 and 4, only the value of the ultrasonic range finder using the water column fluctuated greatly at times. In an ultrasonic range finder using a water column, the measured values are sometimes abnormal if air is involved when the water column touches the slab, this is thought to be the cause of the fluctuations of the range finder values in these experiment.

Fourier transform analysis was applied to the fluctuation of inter-roll bulging and mold level. Figure 6 shows the Fourier transform results. In both results, a peak occurred at a 0.087 (1/s) cycle. In addition, in the analysis of fluctuation of inter-roll bulging, a peak also occurred at a 0.035 (1/s) cycle. The 0.087 (1/s) cycle corresponded approximately to the cycle of the roll pitch divided by the casting velocity.

Figure 7 shows fluctuation of the distance from the ground at the segment including the crater-end position and one segment to the upstream side. At the segment including

Fig. 5. Fluctuation of inter-roll bulging and mold level fluctuation at the same time.

Fig. 6. FFT analysis of inter-roll bulging fluctuation and mold level fluctuation.

the crater-end position, the amount of fluctuation was larger than at the segment one segment to the upstream side, but at both segments, the amplitude of segment fluctuation was smaller than half that of the inter-roll bulging.

Figure 8 shows the results of a Fourier transform applied to the fluctuation of the segment including the crater-end position and the segment one segment to the upstream side. The peak intensity of the cycle corresponding to the

Fig. 7. Fluctuation of relative distance from segment to ground around crater-end segment.

Fig. 8. FFT analysis of segment fluctuation.

roll pitch increased at the segment including the crater-end position compared to the segment on the upstream side. However, the peak intensity shown in Fig. 8 was approximately 1/5 of the peak intensity of the cycle corresponding to the roll pitch in the fluctuation of inter-roll bulging shown in Fig. 6.

Therefore, when a slab with a bulging shape passes through the rolls of a continuous caster, it is considered that the rolls are hardly displaced in the thickness direction, and the liquid phase within the slab is displaced instead. Even in the segment including the crater-end position, although the rolls are displaced slightly in the thickness direction at the cycle corresponding to the roll pitch, this displacement is small compared to the fluctuation of inter-roll bulging. This also supports the conclusion that the liquid phase within the slab is displaced.

The above results revealed that the value measured by the ultrasonic range finder using the water column was the fluctuation of inter-roll bulging as such. In addition, when the amount of fluctuation of inter-roll bulging was compared to the volume change of the mold level, it was found that correction for the segment fluctuation is unnecessary.

Ishimura *et al.*⁸⁾ and Nakamori *et al.*⁹⁾ reported that the fluctuation cycle of the segment and bulging corresponded to the rotation cycle of the rolls. In this study, as shown in Figs. 6 and 8, a peak also occurred at a 0.035 (1/s) cycle in the results of the Fourier transform analysis of the fluctuation of the inter-roll bulging and the segments. As this cycle corresponds to one rotation of the roll in the segment,

it was thought that the roll of this segment was eccentric. In contrast, as shown in Fig. 6, a noticeable peak at 0.035 (1/s) was not observed when the Fourier transform analysis was applied to the fluctuation of the mold level. This means that segment fluctuations due to the eccentric roll had little effect on mold level fluctuations.

3.2. Volume Change by Inter-roll Bulging Fluctuation and Mold Level Fluctuation

The volume change of the molten steel with mold level fluctuations caused by unsteady bulging is supposed to be equal to the volume change of the liquid phase within the slab caused by inter-roll bulging fluctuation. In order to evaluate the validity of the amount of fluctuation of inter-roll bulging measured in this study, the amount of fluctuation of inter-roll bulging was converted to fluctuation of the mold level, and the value was compared to the actual amount of fluctuation of the mold level.

In past studies, it was considered that unsteady bulging becomes larger in case a slab passes continuously through rolls with the same pitch. Yamamoto *et al.*²⁾ shortened the length of the region with the same roll pitch from 8.75 m to 5.25 m.

In the continuous casting machine in the present study, the rolls were also arranged with the same roll pitch, and the region was from the crater-end position to approximately 8.4 m on the upstream side, which included the installation position of the ultrasonic range finder using the water column. Since the fluctuation of inter-roll bulging was measured at only one position in the casting direction in the present study, it was assumed that the amount of fluctuation of inter-roll bulging was the value measured in this study and was constant in the casting direction, as the range finder position was roughly halfway between the crater-end position and the starting point of the region of rolls arranged with the same roll pitch. Mold level fluctuation was assumed to be caused only by unsteady bulging, and other effects such as throughput were ignored.

Figure 9 shows a schematic diagram of the unsteady bulging and mold level fluctuation.

The volume change of the molten steel by mold level fluctuation is expressed by Eq. (1).

$$\Delta V_M = DHW \dots\dots\dots (1)$$

Where, H (mm): amplitude of mold level fluctuation, D

(mm): mold thickness, W (mm): mold width, ΔV_M (mm³): volume change of molten steel by mold level fluctuation.

Next, the volume change of the liquid phase by fluctuation of inter-roll bulging is expressed by Eq. (2).

$$\Delta V_B = 1000 \Delta d W_L L \times 2 \quad (2)$$

Where, Δd (mm): average amount of fluctuation of inter-roll bulging, L (m): length of unsteady bulging occurring in casting direction, W_L (mm): average width of liquid phase at position of unsteady bulging.

Here, the bulging shape is assumed to be a straight line. The average amount of fluctuation of inter-roll bulging is expressed by Eq. (3).

$$\Delta d \equiv 1/2(d_{\max} - d_{\min}) = d/2 \quad (3)$$

Where, $d_{\max}$ (mm): maximum of inter-roll bulging, $d_{\min}$ (mm): minimum of inter-roll bulging, d (mm): amount of fluctuation of inter-roll bulging.

Equation (2) is expressed by Eq. (4).

$$\Delta V_B = 1000 d W_L L \quad (4)$$

Under the assumption that the volume changes calculated respectively using Eqs. (1) and (4) were equal, the fluctuation of inter-roll bulging shown in Fig. 5 was converted to mold level fluctuation. The values in actual casting were used for D and W in Eq. (1), and W_L in Eq. (4) was given by a heat-transfer calculation. L in Eq. (4) was 8.4 m.

The result is shown in Fig. 10. The amount of fluctuation of the mold level converted from the amount of fluctuation

of inter-roll bulging corresponded approximately to the actual amount of fluctuation of the mold level.

Therefore, the absolute amount of inter-roll bulging fluctuation measured in this study is thought to be valid.

4. Discussion

As mentioned above, when unsteady bulging occurs, a slab with a remaining bulging shape passes through the series of rolls in the continuous casting machine. Even when the fluctuation of inter-roll bulging is minimum, the slab is assumed to bulge to some degree because the ferrostatic pressure of the molten steel acts on the slab. Therefore, it is considered that there are two types of relationships between the slab shape and the pass line of the rolls when unsteady bulging occurs, as shown in Fig. 11. Figure 11(a) shows a schematic drawing of the type when the minimum amount of inter-roll bulging is located inside the pass line, and Fig. 11(b) shows a schematic drawing of the type when the minimum amount is located outside the pass line. Past studies also presented schematic drawings of unsteady bulging. For example, the unsteady bulging shown graphically by Matsumiya *et al.*¹²⁾ is thought to be classified as type in Fig. 11(a), while that shown by Lee *et al.*¹⁰⁾ is thought to be classified as the type in Fig. 11(b). The shape of unsteady bulging in this study is estimated from the measured fluctuation of inter-roll bulging.

The fluctuation of inter-roll bulging measured correspond to the difference between the maximum and minimum amounts of inter-roll bulging ($d_{\max} - d_{\min}$). It is considered that unsteady bulging has the shape shown in Fig. 11(a) in case $d_{\min}$ is negative, and has the shape shown in Fig. 11(b) when $d_{\min}$ is positive. $d_{\max}$ is assumed to correspond to the value calculated by the calculation formula for the amount of inter-roll bulging proposed heretofore.

Based on an elastic beam model, Kawawa *et al.*¹³⁾ proposed the calculation formula shown in Eq. (5) for the maximum deflection value.

$$\delta = 60 / 384 \times P l^4 / E d_{\text{shell}}^3 \quad (5)$$

Where, δ (cm): maximum deflection value, P (kg/cm²): ferrostatic pressure, l (cm): roll pitch, E (kg/cm²): Young's

Fig. 9. Schematic drawing of unsteady bulging and mold level fluctuation.

Fig. 10. Comparison of converted MD level and actual MD level.

Fig. 11. Schematic drawing of unsteady bulging shape, (a) $d_{\min} < 0$, (b) $d_{\min} > 0$.

modulus, d_{shell} (cm): solidified shell thickness.

Morita *et al.*¹⁴⁾ proposed a bulging amount based on a stress analysis using the finite element method, as shown in Eq. (6).

$$\delta = P / 220 \times 10^{3.5} / d_{\text{shell}}^3 \dots\dots\dots (6)$$

In the present study, d_{max} was calculated by these formulas. The thickness of the solidified shell was the value calculated by a heat-transfer calculation at the measurement position of bulging in this study. The ferrostatic pressure and roll pitch were also the values at the measurement position of bulging in this study. $d_{\text{max}} - d_{\text{min}}$ was calculated by averaging the difference between the maximum and minimum values in the cyclic fluctuation of inter-roll bulging shown in Fig. 5.

As a result, d_{min} had a negative value. Therefore, when the inter-roll bulging was the minimum value, the slab shape was considered to be concave inside pass line, as shown in Fig. 11(a) in this study.

5. Conclusion

The amount of fluctuation of inter-roll bulging in a commercial continuous casting machine was measured in consideration of the fluctuation of the segment, and was compared to the cycle and volume of the mold level fluctuation. The following results were obtained.

(1) The amount of segment fluctuation was much smaller than the amount of fluctuation of inter-roll bulging. Therefore, segment fluctuation did not affect the measured results of inter-roll bulging fluctuation.

(2) Inter-roll bulging and the mold level fluctuated with

the same cycle, and this cycle corresponded to the cycle calculated from the roll pitch and casting speed. Therefore, it was confirmed that the value measured by an ultrasonic range finder in this study was unsteady bulging as such.

(3) The amplitude of the mold level converted from the fluctuation amount of inter-roll bulging corresponded approximately to the actual mold level. Therefore, the absolute amount of inter-roll bulging fluctuation measured in this study was considered reasonable.

(4) When the inter-roll bulging was the minimum value, the slab shape was considered to be concave inside pass line in this study.

REFERENCES

- 1) T. Kato, K. Ishii, S. Kohira, J. Kubota and K. Tsutsumi: *CAMP-ISIJ*, **17** (2004), 853.
- 2) H. Yamamoto, K. Matsumura, A. Yamagami, N. Tsuru, T. Sera and A. Yoshii: *Tetsu-to-Hagané*, **73** (1987), S913.
- 3) T. Saeki, H. Imura, Y. Onishi, H. Niimi, H. Miwa, T. Yoshida, S. Igari and S. Kitamine: *Tetsu-to-Hagané*, **69** (1983), A205.
- 4) S. Maeno, K. Wada, Y. Itoh and Y. Nagano: *Tetsu-to-Hagané*, **69** (1983), S938.
- 5) K. Kataoka and M. Ito: *Denki Seiko*, **77** (2006), 241.
- 6) H. Fujii, T. Ohashi, M. Oda, R. Arima and T. Hiromoto: *Tetsu-to-Hagané*, **67** (1981), 1172.
- 7) T. Kanazawa, Y. Sugitani, M. Nakamura and J. Y. Lamant: *Tetsu-to-Hagané*, **70** (1984), S898.
- 8) S. Ishimura, I. Kato, S. Kobayashi, T. Adachi and T. Yamada: *Tetsu-to-Hagané*, **65** (1979), S713.
- 9) Y. Nakamori, T. Kawaguchi, H. Soga and K. Minami: *Tetsu-to-Hagané*, **67** (1981), S903.
- 10) J. D. Lee and C. H. Yim: *ISIJ Int.*, **40** (2000), 765.
- 11) U. S. Yoon, I. W. Bang, J. H. Rhee, S. Y. Kim, J. D. Lee and K. H. Oh: *ISIJ Int.*, **42** (2002), 1103.
- 12) T. Matsumiya: *ISIJ Int.*, **46** (2006), 1800.
- 13) T. Kawawa, H. Sato, S. Miyahara, T. Koyano and H. Nemoto: *Tetsu-to-Hagané*, **60** (1974), 486.
- 14) Y. Morita, H. Kawashima and M. Nakamura: *Sumitomo Met.*, **35** (1983), 271.