1. Introduction

Strand deformation from bulging is one of the main phenomena that cause defects such as internal cracks and segregation in the continuous casting of steel. Since the parameters that affect bulging are not essentially constant during casting, the behavior of slab bulging is rather unsteady \(^1\)–\(^4\) than steady, therefore, bulging profile changes with time. When the fluctuation of bulging with time (called unsteady bulging) is very large, it may lead to serious fluctuations in the mold level. This results in the increase of defects \(^1\)–\(^3\) or even breakouts, and a possible stop in the casting process.

However, many researches have mainly focused on steady bulging \(^5\)–\(^13\) rather than unsteady bulging. So its origin and detailed mechanisms have not been verified and even measurements has been limited. Unsteady bulging seems to be related to the design of the continuous caster, particularly the layout of the roll-pitch, \(^2\) and certain steel grades such as medium carbon steel. \(^3\) In order to produce defect free or high quality steel, this needs to be investigated both theoretically and experimentally to meet the requirements for a stable operation of continuous casting without fluctuations in the mold level.

In this paper, the movements of the driven rolls were measured during casting with the use of the displacement transducer (LVDT) and compared with other signals such as the casting speed and the mold level. The bulging profile over several roll pitches with time was analyzed for the two-dimensional finite element model and then compared with experimental results. Based on the results from these calculations and experiments, the origin and the characteristics of unsteady bulging were discussed.

2. Experimental Procedures

In continuous casting, driven rolls (or pinch rolls) are used to withdraw the slab, and can be pressure- or position-controlled. Particularly in the pressure-controlled case, its position seems to sensitively change with time because of the variation of the bulging that may cause a fluctuation in the withdrawal resistance. Therefore, instead of measuring the bulging, the movement of the driven rolls was measured with the use of the displacement transducer (LVDT). The transducer was installed inside the specially designed apparatus where dry air was used for purging. The movements were measured for the driven rolls located at 10.7 m, 14.5 m and 26.5 m from the meniscus level. The currents of the driven roll, the casting speed and the mold level were measured and their fluctuations were compared with the movements of the driven roll. In order to investigate a shell profile within the mold, FeS powders were inserted into the molten steel where sulphur was segregated at the interface between the solidified shell and the liquid steel. After casting, the shell profile was observed metallographically using the Sulfur print technique.
2.1. Analysis of Unsteady Bulging in the Model Over the Successive Rolls

A two-dimensional model over the successive rolls was used to calculate the bulging profile and its changes with time, during the fluctuations in the casting speed, with the Marc FEM code. As depicted in Fig. 1, the thickness of the slab was 55 mm, the surface temperature was 950°C, and roll pitch varied from 272 to 377 mm. As boundary conditions, the $x$ displacement at the left and right edges and the $y$ displacement at the surface point of each edge of the slab were assumed to be zero. The value around the center position, which is not affected by boundary conditions, was used to evaluate the bulging behavior. In addition, a roll was assumed to be a rigid body. The period of fluctuation in the casting speed was assumed to be 16.16 sec and 11.66 sec which corresponds to 377 mm and 272 mm roll pitches respectively, under casting speeds of 1.46.05 m/min.

With respect to the material properties of the slab, an appropriate flow equation was established as following form.

$$\sigma = C \cdot \exp\left(\frac{Q}{RT}\right) \cdot \varepsilon^n \cdot \dot{e}^m$$

In this equation, $\sigma$ is the flow stress, $\varepsilon$ is the true strain, $R$ is the Boltzmann constant, $T$ is the absolute temperature, and $C$, $Q$, $n$, $m$ were determined by the compressive test, where flow stresses of the medium carbon steel were obtained in temperatures ranging from 850 to 1200°C. The composition of the steel tested is represented in Table 1.

| C  | Si | Mn | P  | S  | Ca | Ni | Nb | V  | Ti | TotAl |
|----|----|----|----|----|----|----|----|----|----|-------|
| 0.113 | 0.282 | 0.89 | 0.019 | 0.007 | 0.01 | 0.02 | 0.002 | 0.003 | 0.001 | 0.032 |

3. Experimental Results

3.1. Relation between the Signals and the Uneven Thickness of the Solidified Shell

The movements of the driven roll, the liquid steel level, the casting speed and the current of the driven roll were measured for the same driven roll located at 14.5 m from the meniscus level. The results are shown in Fig. 2. There seems to be a certain correlation between these signals. With the use of the FFT technique, it was verified that the liquid steel level has an only frequency close to the roll pitch (0.092 Hz) and that the other three signals seem to have two main frequencies of the roll pitch and the roll rotation (0.029 Hz). The casting speed has a similar tendency with the movement of the driven roll and has a reverse correlation with the current of the driven roll. Because bulging may increase the withdrawal resistance, resulting in the decrease in the casting speed and the increase in the current of the driven roll, this is believed to have a reverse correlation with the movement of a driven roll with the same frequency. The values in the movement of the driven roll represent the relative value with the zero position (or reference position) for non-casting stage. Therefore, the negative sign means the negatively-misaligned status of the driven roll, and the positive sign means the positively-misaligned status.

As shown in Fig. 3, a large fluctuation in the movement of the driven roll is frequently observed during the casting of medium carbon steel, particularly in 0.09–0.11% carbon steel. The solidified shell profile within the mold was measured by the method described in the experimental results. As a result, the very uneven thickness of the solidified shell along the casting direction was obtained only in the carbon range stated above and the result is shown in Fig. 4. The white region represents the solidified shell, and the dark region represents the sulfur-segregated region, which was the liquid region within the mold during the casting. The frequency of the unevenness in the thickness of the shell was
3.2. The Results of Unsteady Bulging Analysis

As mentioned above, fluctuations in the movement of the driven roll, which may be due to the time dependent bulging (unsteady bulging), is accompanied by fluctuations in the casting speed. Therefore, in order to induce unsteady bulging in the calculations, the casting speed was assumed to vary with a period of 16.16 or 11.66 sec which corresponds to a roll pitch of 377 or 272 mm respectively under an average casting speed of 1.4 m/min.

Figure 5 shows the bulging profile made by the point that started from the 301 site, and its variations calculated under a period of 16.16 sec which corresponds to a roll pitch of 377 or 272 mm respectively under an average casting speed of 1.4 m/min.

Figure 6 shows the result in the case of a period of 11.66 sec that corresponds to a roll pitch of 272 mm. The phases of unsteady bulging are not the same within the same roll pitches of 377 mm. The bulging phase also changes after the roll pitch changes from 333 to 377 mm.

4. Discussion

4.1. The Origin of Unsteady Bulging

Using the FFT technique, a frequency analysis was performed for the movements of the two driven rolls which were located at 10.7 m and 26.5 m. In the case of low carbon steel, the results are shown in Fig. 7. It is composed of two kinds of frequencies, which are the roll rotation and the roll pitch. The peak representing the roll rotation is very sharp while the peak representing the roll pitch is rather broad. In the case of medium carbon steel, in which a large fluctuation occurs, the result of the frequency analysis shows another sharp frequency which lies in the range of 0.2 to 0.3 Hz as shown in Fig. 3. This range in the frequency is probably not due to the structure of the continuous caster. Lamant et al. observed frequencies of 0.1–0.5 Hz with high mold level amplitude in medium carbon steel. These frequencies were often very close to 0.3 Hz and based on the observation of deep oscillation mark, it was concluded to be the results of the uneven solidified shell. And, Singh and Blazek obtained uneven solidified shell along the casting direction in controlled breakout experiments. In the meantime, Grill and Brimacombe have proposed a mechanism for the formation of an uneven solidified shell which is caused by the periodical formation of air gap due to δ→γ transformation. In this study, a very uneven solidified shell was also observed during the casting of medium carbon steel, as shown in Fig. 4. As mentioned in the experimental results, the period of unevenness in the thickness of the solidified shell lies between 0.2–0.4 Hz and
Fig. 5. Calculated results of the bulging profile over successive rolls and its variation with time caused by periodical variations in the casting speed. (The fluctuation period of the casting speed is: 377 mm, 16.16 s.)

Fig. 6. Unsteady bulging variation according to periodical variations in the casting speed. (The fluctuation period of the casting speed is: 272 mm, 11.66 s. Note the phases of unsteady bulging are not the same in the region of the same roll pitches.)

Fig. 7. Comparison of frequencies between two different rolls pitches. (a) Roll pitch: 275 mm (b) Roll pitch: 343 mm (Details are given within each figure.)
is similar to the sharp frequency of 0.2–0.3 Hz observed when large unsteady bulging occurs in medium carbon steel. Therefore, it could be concluded that unevenness in the thickness of the solid shell is one of the origins of unsteady bulging during the casting of medium carbon steel whose carbon range is around 0.1%. The reason why unsteady bulging is severe in 0.09–0.11% carbon remains to be studied in the future.

4.2. The Characteristics of Unsteady Bulging and Its Relation to the Fluctuation in the Mold Level

As shown in Fig. 8, when the period of the casting speed is 16.16 sec, which corresponds to a roll pitch of 377 mm, the period of the unsteady bulging at the site of the roll pitch of 377 mm is close to this period of the casting speed. However, the period of unsteady bulging at 333 site is much closer to that of a roll pitch of 333 mm (14.27 sec) than that of the casting speed. As shown in Fig. 9, when the period of the casting speed is equal to a roll pitch of 272 mm (11.66 sec), the period of unsteady bulging at the 377 site is still equal to that of a roll pitch (16.16 sec). To summarize, the period of unsteady bulging is close to that of the roll pitch regardless of the period of the casting speed. However, it appears to be somewhat affected by a casting speed variation. This is concluded from the fact that phases of unsteady bulging are not the same within the region of same roll pitches when, as discussed in the experimental results, the period of the casting speed is not equal to that of the roll pitch. In Fig. 7, it could also be experimentally verified that the frequency of unsteady bulging at each site depended on the roll pitch of each site, resulting in 0.098 Hz for a roll pitch of 275 mm (10.7 m from the meniscus) and 0.071 Hz for a roll pitch of 343 mm (26.5 m from the meniscus). Therefore, the results calculated using the FEM are in good agreement with the experimental results obtained by measuring the movement of the driven roll in real caster.

From the above results, it could be concluded that the phase of the bulging is greatly influenced by the period of the roll pitch and is somewhat affected by the period of the casting speed. Regarding the effect of unsteady bulging on the fluctuation in the mold level, if the phase of unsteady bulging at each roll pitch site is the same, a large change in the volume of the liquid steel inside the slab will occur and result in a large fluctuation in the mold level, as depicted in Fig. 10(a). If the phases are different, the change in the volume of the liquid steel at each site compensates one another, resulting in a small fluctuation in the mold level, as shown in Fig. 10(b). In order to formulate the effect of unsteady bulging on the mold level, the period of unsteady bulging was assumed to be equal to the period of the roll pitch and assumed not to be influenced by other factors such as casting speed variations. In addition, it was assumed that the bulging profile is described by a sine function and the initial bulging phase at each site is the same. Therefore, the fluctuation in the mold level caused by unsteady bulging is described by regarding a bulging area as a triangle as follows.

$$H(t) \cdot D = -2 \sum_{i} \frac{L_i}{2} \cdot \left( \frac{\delta_{\text{max}} - \delta_{\text{min}}}{2} \right) \cdot \sin \left( \frac{2\pi}{L_i} \cdot t \right) \quad \ldots (2)$$

Where, $H(t)$ is the level fluctuation, $D$ is the thickness of the slab, and $L_i$ is the roll pitch.
the slab, \( L_i \) is the roll pitch at the \( i \) site, \( \delta_{\text{max}} \) is the maximum amount of bulging at the \( i \) site, \( \delta_{\text{min}} \) is the minimum amount of bulging at the \( i \) site, \( t_{Li} \) is the period of unsteady bulging at the \( i \) site and \( t \) is the time. Since \( t_{Li} \) has more than one value and the fluctuations of the other parameters, such as the casting speed or the change of the roll pitch, also affect the phase of unsteady bulging, the actual relation is more complicated. Basically, the fluctuation in the mold depends on many parameters, it is very difficult to show the direct result of application of the Eq. (2) that shows only how different roll pitch configurations affect the fluctuation in the mold relatively. Meanwhile, the change in the fluctuation in the mold has been evaluated for the cases before and after the change in the roll pitch configuration, and has been verified from the actual experience in POSCO. Therefore, Eq. (2) would be useful to evaluate the fluctuations in the mold caused by unsteady bulging under the different conditions of the roll pitch configuration.

Though the unsteady bulging has two kinds of frequencies which are the roll pitch and the roll rotation, as shown in Fig. 2, only the roll pitch affects the mold level. Since the phases of the unsteady bulging due to the roll rotation are essentially at random, the change in the volume of the liquid steel at each site compensates one another, resulting in a negligible effect on the fluctuation in the mold level.

5. Summary

The movement of the driven roll was measured and its fluctuation was compared to the casting speed, the mold level and the periodical variation in the thickness of the solid shell. With the use of the FEM, the change in the bulging profile with time was calculated with the fluctuation in the casting speed. The following results were obtained.

(1) Frequency analysis shows two kinds of frequencies of the roll rotation and the roll pitch for low carbon steel. It also shows an additional sharp frequency of 0.2–0.3 Hz for medium carbon steel in which a large fluctuation frequently occurs. This additional frequency was explained by the periodical variation in the thickness of the solid shell along the casting direction.

(2) As a result of the calculations with the FEM, it is concluded that the period of unsteady bulging is greatly influenced by the roll pitch and is close to that of the roll pitch. It could also be experimentally verified that the frequency of unsteady bulging depends on the locations where different roll pitches occur. This results in frequencies of 0.098 Hz for a roll pitch of 275 mm and 0.071 Hz for a roll pitch of 343 mm. Therefore, the results calculated with the FEM are in good agreement with the experimental results obtained by measuring the movement of the driven roll in real caster.

(3) However, based on the calculation results, the phase of unsteady bulging is somewhat affected by the variations in the casting speed, because the phases of unsteady bulging are not the same within the region of the same roll pitches, when the period of casting speed is different from that of the roll pitch. In addition, in the region where the roll pitch changes, the phase of unsteady bulging changes as well.

(4) The fluctuation in the mold level depends on the phase of the unsteady bulging. If, as in the case of the same roll pitches, the phases are the same, a large change in the volume of the liquid steel inside the slab will occur and result in a large fluctuation in the mold level. If, as in the case of the roll rotation, the phases are at random, the effect of this on the mold level is small or sometimes negligible.

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