Internal Defects of Continuous Casting Slabs Caused by Asymmetric Unbalanced Steel Flow in Mold

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The molten steel flow in the continuous casting mold and entrapment of inclusions and bubbles on the inner surface of the solidified shell are examined to clarify the origin of internal defects in steel products. Defects on steel sheets are caused by inclusions and bubbles entrapped on the solidified shell during casting. It was found that bubbles are able to penetrate deeply due to an unbalanced time-dependent flow. This phenomenon can be explained by the Large Eddy Simulation model, which is capable of simulating the time-dependent flow.

The number of inclusions increases as the bubble diameter and the distance of the position of entrapment from the top free surface increase. This indicates that bubbles collect inclusions while traveling in the molten steel in the continuous caster. A simple mathematical model is presented to explain how the inclusions are collected by bubbles.

The calculation results also reveal that the static magnetic field generated by the FC Mold reduces time-dependent flow changes and thereby prevents internal defects caused by bubbles and inclusions.

KEY WORDS: continuous casting; molten steel; casting mold; entrapment; bubble; inclusion; solidified shell; internal defect; magnetic field.

1. Introduction

The flow of molten steel in the continuous casting mold is of great interest because of its influence on many important phenomena related to product quality, including entrapment of inclusions and bubbles on the solidified shell, which causes internal defects in cast slabs and various defects in final products.

The continuous casting process with the vertical-bending type machine has far fewer internal defect problems than the same process with the curved type caster. However, even with the vertical-bending caster, defects are still a problem in high quality steel products, such as sheets for deep drawing use.

It may be assumed that large bubbles tend not to penetrate into the deep region of the molten steel strand because they have a large buoyancy force. However, bubbles in the 1–3 mm size range are sometimes found in cast slabs.

Fundamental work on the entrapment of particles on the solidified shell has shown that the so-called “washing effect,” which occurs in high speed casting, can reduce the number of particles entrapped on the shell.1–3) Theoretical models not to take macro steel flow into account, have also been published,4) and a new research has demonstrated that the thermal conductivity of particles is important for entrapment probability.5,6)

Al₂O₃ particles are usually observed on the surface of bubbles in cast steel, where they seem to coagulate. This suggests that the presence of bubbles accelerates coagulation and thus encourages the formation of larger Al₂O₃ clusters.

However, in any case, the mechanism of internal defects has not yet been sufficiently clarified. At present, it can only be said with certainty that internal defects are caused by bubbles and inclusions entrapped on the shell.7)

In order to clarify the mechanism of internal defects caused by bubbles and inclusions, the authors carried out a fundamental examination of the entrapment of inclusions and bubbles on the solidified shell of molten steel during continuous casting using water model experiments and a numerical fluid flow simulation. Particular attention was given to the unbalanced time-dependent flow in the mold and attachment of inclusions to bubbles.

The FC mold,8) which consists of two magnetic coils, generates homogeneous magnetic field on the large area. The upper field is for stabilising the top free surface and the lower one seems to be effective for suppressing the downward steel. So, the effect of a static magnetic field on the time-dependent flow was also estimated by numerical simulation.

2. Internal Defects

Some internal defects in steel products are caused by entrapped bubbles and inclusions, which originate as far upstream as the continuous casting process. For example, blister defects are caused by bubbles and surrounding Al₂O₃ particles. Figure 1 shows an example of internal defects in a cold rolled sheet. The depth from the slab surface is estimated to be about 10–20 mm. Based on observation of cast
slabs, the diameter range of entrapped bubbles is usually 0.5–3.0 mm. Hydrogen atoms concentrate on these bubbles during annealing, causing the bubbles to expand. In addition, Al₂O₃ clusters attached to bubbles are generally much larger than independent Al₂O₃ clusters because Al₂O₃ particles tend to coagulate on bubbles, as suggested by Shibata et al.⁹)

On the other hand, it may also be proposed that if only bubbles existed in a slab, without associated inclusions, these bubbles alone would not cause internal defects because rolling can adequately close up simple gaseous porosities.

3. Experimental Method

3.1. Water Model Experiment

A water model experimental apparatus of the same size as an actual casting mold is shown in Fig. 2. The strand thickness and width were 220 mm and 1,500 mm, respectively. The strand height was designed to be 3 m to reduce the influence of the bottom. The flow velocity at the center of thickness at the 1/4 width position (M1) and the flow velocity near the short edge at a point 1 m below the surface (M2) were measured with a propeller-type velocity meter. The margin of error of the propeller velocity meter was 0.01 m/s. Approximately 4,000 data were sampled over a period of 800 s at intervals of 0.2 s.

3.2. Calculation Method

The molten steel flow was calculated using a commercial code called Fluent.¹⁰) A Large Eddy Simulation (LES)¹¹) with a Smagorinsky sub-grid-scale model was employed to calculate the time-dependent flow. In an unsteady state simulation, only large eddies to which momentum and mass were transported were calculated by the LES, and small eddies to which energy was dispersed were solved using the $k$–$ε$ model.

Turbulence viscosity is expressed by Eqs. (1) and (2).

\[ \mu = \rho L_s^3 |\mathbf{S}| \] ........................(1)

\[ L_s = \min(\kappa d, C_s V^{1/3}) \] ........................(2)

Here, $\rho$: density (7,000 kg/m³), $L_s$: mixing length, $\mathbf{S}$: strain rate tensor, $\kappa$: constant (0.42), $d$: distance from nearest wall, $C_s$: Smagorinsky constant (0.1), $V$: volume of cell.

Since the jet flow velocity is large, the influence of thermal convection was disregarded. The model was divided
into 140,000 meshes for a 1/2 symmetrical model. The influence of gas bubbles on the steel flow was considered according to the Dispersed Phase Model (DPM). In this experiment, 1,000 bubbles per time-step were released from the top of the nozzle. The bubble diameter distribution was assumed to be \( N \) in Eq. (3) based on measured results reported in the literature.

\[ N = AD^{-5} \] .................................. (3)

Here, \( N \): number of bubbles, \( A \): constant, and \( D \): diameter of bubbles.

It is assumed that inclusions and gas bubbles which reached the free surface of the molten steel were separated by flotation. The maximum time-step was 0.0125 s.

To simulate the flow under a static magnetic field, the magnetic induction method shown in Eq. (4) was employed.

\[ \frac{\partial B}{\partial t} + (U \cdot \nabla)B = \frac{1}{\mu \sigma} \nabla^2 B + (B \cdot \nabla)U \] ............ (4)

Where, \( B \) is the sum of the magnetic field imposed by the electromagnet, \( B_0 \), and the magnetic field induced by the steel flow, \( b \). The symbols \( \mu \) and \( \sigma \) are the magnetic permeability and the electrical conductivity of steel, respectively.

The velocity derived from the water model can be compared to the results of the numerical simulation or actual mold flow since all cases are the same in size and kinematic viscosity of fluid.

3.3. Investigation of Bubbles in Slab

The bubble distribution in cast slabs was investigated by the X-ray transmission method at a cross section perpendicular to the casting direction. The number of \( \text{Al}_2\text{O}_3 \) particles adhering to the surface of a bubble was counted by SEM observation.

4. Results

4.1. Water Model Experiments

Observation of the water model revealed the existence of an asymmetric unbalanced time-dependent flow, as shown in Fig. 3. This means that the steel flow rate from one spout is not always the same as that from the other. These phenomena seem to be due to instability of the flow.

Figure 4 shows the measured flow velocity of points M1 and M2. Both the velocity at M1 and at M2 fluctuated.

Fig. 3. Observation of bubble distribution in mold (throughput: 6.0 t/min, gas flow rate: 10 L/min).

Fig. 4. Measured flow velocity at position M1 and M2 (throughput: 6.0 t/min, gas flow rate, 10 L/min).

Fig. 5. Results of FFT analysis (throughput: 6.0 t/min, gas flow rate: 10 L/min).
Fast Fourier Transform (FFT) analysis was applied to estimate the frequency of the fluctuation of the flow velocity. Figure 5 shows examples of the analysis results. There is a clear peak around 15 s, and the period of the peak is shorter with larger molten steel throughputs, as shown in Fig. 6. On the other hand, there were no clear peaks without gas blowing, as shown in Fig. 7.

4.2. Calculation Results

Figure 8 shows the calculated results of the velocity vector and trajectories of 1 mm diameter bubbles. Fig. 8(a) is the time-averaged flow velocity, and Figs. 8(b) and 8(c) show the time-dependent unbalanced flow. Here, Fig. 8(c)
shows the flow at 15 s after Fig. 8(b). Figure 8(d) shows the result calculated by the $k$–$\varepsilon$ model. In Fig. 8(c), eddies near the nozzle can be realized, which might cause engulfment of the mold flux.

Based on the velocity vector of the molten steel and trajectories of bubbles with a 1 mm diameter, trajectories with a time-averaged flow cannot explain the penetration of bubbles into the deep region of the molten steel, which was observed in the water model. That is, in a time-averaged steel flow, bubbles do not overcome the force of buoyancy and therefore cannot penetrate into the deep region. Rather, the bubbles easily rise to the surface, where they dissipate into the atmosphere. In contrast to this, in the unsteady time-dependent flow simulation results, some bubbles penetrated to a depth of more than 1.5 m below the surface. The trajectories calculated by the $k$–$\varepsilon$ model shown in Fig. 8(d) are slightly different from those of the time-averaged flow shown in Fig. 8(a), but all the bubbles rose to the top surface, even with the $k$–$\varepsilon$ model.

An example of the flow velocity calculated for points M1 and M2 is shown in Fig. 9. The mean, maximum, and minimum values are almost identical with the measured values shown in Fig. 4. The FFT of the calculated velocity was also compared with the measured results, and a similar fluctuation period of 15 s was obtained.

Figure 10 shows the velocity vector calculated on the assumption that a DC magnetic field of 0.3 T is imposed. Figure 11 shows the calculated and flow velocity fluctuations measured at the M1 point in the continuous casting mold. The fluctuation is much less than that without the DC magnetic field. This phenomenon is attributable to the large braking force acting on the high velocity steel.

### 4.3. Distribution of Bubbles in Slab and $\text{Al}_2\text{O}_3$ in Bubbles

Figure 12 shows the results of an investigation of bubble distribution by the X-ray transmission method in a sample cut out perpendicular to the casting direction. For comparison purposes, bubbles which were detected in two samples separated by a distance of 0.2 m in the casting direction are superimposed on the same drawing. More bubbles were observed in the region within 0.3 m from the narrow face than at the center of width.

The number of $\text{Al}_2\text{O}_3$ particles on the bubble surface was counted by SEM observation, as shown in Fig. 13. A few hundred $\text{Al}_2\text{O}_3$ particles are found on the surface of one bubble.

### 5. Discussion

#### 5.1. Penetration of Bubbles

The position where a bubble was entrapped on the solidified steel shell in the casting mold is calculated based on its distance from the surface of the slab. The solidification coefficient was assumed to be $21 \text{ mm/min}^{-0.5}$ in the mold and $28 \text{ mm/min}^{-0.5}$ in the secondary cooling zone. Thus, these bubbles were estimated to be entrapped at positions 2–6 m from the surface, as shown in Fig. 14.
Comparing the water model experiment results and the calculated results, the above-mentioned depth of 2–6 m is similar to the maximum penetration depth of bubbles in the water model. Furthermore, few bubbles were trapped at the area of initial solidification in the mold, even though the number of bubbles is much greater near the free top surface than in the deeper region. This is considered to be due to the “washing effect” of the steel flow, by which the large flow velocity at the inner shell near the top free surface suppresses entrapment. In the deeper region, for example, 6 m from the free surface, the flow velocity is small and as a result, bubbles are easily entrapped on the shell if they are once carried to this depth by an unbalanced flow.

Since the static magnetic field generated by the FC (Flow Control) Mold\textsuperscript{15} reduces both changes of time-dependent flow and the absolute value of the flow velocity, the FC Mold is effective in preventing penetration of bubbles into deep region from the top surface and entrapment on the shell. Thus, it reduces internal defects caused by bubbles and inclusions.

5.2. Al\textsubscript{2}O\textsubscript{3} Particles on Bubbles

In many cases, Al\textsubscript{2}O\textsubscript{3} particles are observed on the inner surface of the bubbles in slabs. These particles are considered to be caught by the bubbles due to the velocity difference between the particles and the bubbles in a molten steel flow.

The inclusion adhesion rate for an Ar bubble is calculated by assuming a streamline flow of molten steel around the bubble. The streamline is calculated by Eq. (5), assuming the potential flow:\textsuperscript{16}

$$\varphi = \frac{1}{2} U \sin^2 \theta \left( R^2 - \frac{a^2}{R} \right) \quad \text{equation}(5)$$

Fig. 11. Calculated and measured surface flow velocity with static magnetic field.

Fig. 12. Position of entrapped bubbles on cross section.

Fig. 13. SEM images of bubbles and Al\textsubscript{2}O\textsubscript{3} particles.
Here, \( y \): stream function, \( U \): flow velocity of steel, \( a \): bubble radius, and \( R \): spherical polar coordinates.

The streamline around a bubble with 5 mm diameter is shown in Fig. 15. The weight of particles caught by the bubble is calculated assuming that the bubble travels in molten steel with homogenously dispersed oxide particles, and can be expressed by Eq. (6).

\[
M = 3.3 \times 10^{-7} D_{\text{bub}} O_{\text{ppm}} L 
\]  

(6)

Here, \( M \): weight of particles caught by a bubble (kg), \( D_{\text{bub}} \): diameter of a bubble (m), \( O_{\text{ppm}} \): oxygen content of steel (ppm), and \( L \): distance of bubble movement (m).

The number of Al\(_2\)O\(_3\) particles on the bubble surface increases when the bubble is entrapped on the shell at a deeper position, that is, further from the top surface of the molten steel, or when the bubble is large, as shown in Eq. (6).

The distance from the steel free surface, \( L \), and the measured bubble diameter, \( D \), were multiplied, and the counted number of Al\(_2\)O\(_3\) particles was plotted against \( D \times L \), as shown in Fig. 16.

The number of Al\(_2\)O\(_3\) particles in a bubble seems to be proportional to \( D \times L \), which corresponds qualitatively to Eq. (6). This also means that particles tend to collect on bubbles as the bubbles travel through the molten steel in the continuous caster.

Based on Eq. (6), it can be calculated that 6.6 \( \mu \)g of particles become attached to a bubble when a bubble 1 mm in diameter travels a distance of 1 m in molten steel with a 20 ppm oxygen content. Assuming that all Al\(_2\)O\(_3\) particles have a 5 \( \mu \)m diameter, approximately 45 000 of these particles should be observed on the bubble. However, only a few percent of the calculated number of particles will actually be caught on the bubble, even if the number of particles is assumed to be several times greater than that actually observed in the half plane observed with the SEM.

Bubble attachment behavior, as it relates to reduction in the number and size of inclusions, was discussed in a previous work that proposed an inclusion size distribution model for RH degassing. The measured size distribution change can be explained if the probability of entrapment of Al\(_2\)O\(_3\) on bubbles relative to the total collision rate between bubbles and particles is assumed to be 3%. With the results of the two cases described above, the possibility of entrapment is considered to be quite low compared with that given by Eq. (6), probably because the bubble trajectories are superimposed to a considerable extent.

Thus, it seems that further theoretical and experimental examination is necessary before the entrapment of inclusions on bubbles in molten steel can be quantitatively estimated.

6. Conclusion

The flow velocity of an unbalanced time-dependent flow was evaluated by water model experiments and numerical analysis. Bubbles and Al\(_2\)O\(_3\) particles in a cast slab were investigated for comparison with the estimated results. The following findings were obtained.

(1) The flow velocity fluctuates, and these fluctuations include a wide range of flow velocities as large as 0–0.6 m/s. The period of these fluctuations was estimated to be around 15 s based on the water model experiments. The calculated results of the average velocity and the peak of the FFT analysis coincided with the measurements.

(2) The position of entrapped bubbles ranges between 2 and 6 m below the free surface. This penetration depth is not consistent with a time-average flow calculation, but can be explained by the unbalanced time-dependent flow calculation mentioned above.

(3) The number of caught Al\(_2\)O\(_3\) particles increases when a bubble is caught at a deeper position, far from the molten steel surface, or when the bubble is large. The num-
ber of Al₂O₃ particles on a bubble is proportional to \(D \times L\), which corresponds qualitatively to Eq. (6). This also means that particles tend to collect on bubbles as the bubbles travel in the molten steel in the continuous caster.

(4) Since the static magnetic field generated by the FC Mold reduces both the time-dependent flow changes and the absolute value of the flow velocity, the FC Mold is effective in preventing internal defects caused by bubbles and inclusions, as shown in the simulation results.

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