Solidification Mechanism of Thin Slab Cast by Horizontal Twin-belt Caster with Stationary Mold Plate*

By Seiji ITOYAMA,** Nagayasu BESSHO,** Tetsuya FUJII,** Tsutomu NOZAKI*** and Takashi KUSABA**

Synopsis

In order to study fundamental technologies required for thin slab casting, the solidification mechanism in a mold has been investigated by the use of thin slab of 30 mm X 100 mm cast at withdrawal speed of 3.8 to 5.1 m/min with a laboratory scale twin-belt caster. In the caster, a movable steel belt is used as the wide face and a stationary copper plate as the narrow face. From the observation of thin slab cast, it has been concluded that the solidified shell is formed continuously at the wide faces and intermittently at the narrow faces. The occurrence frequency of ripple marks observed on the narrow face is related to the connecting condition between the nozzle and the stationary plate, the tensile strength of the shell and the friction force in the mold. Countermeasures against the occurrence of corner and transverse cracks are discussed in connection with the ripple mark and the brittleness of the γ grain boundary in coiling practice of thin slab cast.

Key words: continuous casting; thin slab; solidification mechanism; belt; cold shut crack; coiling.

I. Introduction

Prevention of surface defects of cast are indispensable for the success in thin slab casting, because the defects cause serious decreases in yield and productivity. In order to improve the slab surface, it is necessary to make the solidification mechanism clear. Therefore, several methods1~8 of thin slab casting have been investigated to develop fundamental technologies required for thin slab casting.

The authors have also investigated the solidification characteristics of thin slab cast by the horizontal twin-belt continuous caster with stationary mold plate, KCC, which was developed in a laboratory scale at the investigation of heat transfer in a mold.7,8 The mold construction of KCC is characterized by the use of a pair of movable steel belts as the wide face, and a pair of stationary copper plates as the narrow face. The ripple marks similar to the so-called cold shut mark9 appeared on the surface of billet cast by a conventional horizontal caster with intermittent withdrawal using break ring are observed on the narrow face of the thin slab cast. Therefore, it is supposed that the solidification mechanism of thin slab in KCC mold is not the same with those of conventional horizontal continuous caster and Hazelett machine.10 The ripple marks seem to induce cracks on coiling or rolling of thin slab cast.

From this reason, the present paper deals mainly

II. Experimental Procedures

1. Casting Method

Figure 1 shows the schematic drawing of the horizontal thin slab caster, KCC, used in this experiment. The casting mold of KCC consists of a pair of movable steel belts with water-cooled pads, which are comprised of the upper and lower wide faces of the mold and are synchronized with strand, and a pair of stationary water-cooled copper plates as the narrow face. Moreover, a refractory nozzle is contacted with the belts and stationary plates. The steel belt is made of cold rolled sheet of low carbon aluminum killed steel and is 0.8 to 0.9 mm thick. The cooling length of the belt is 1.1 m and the length of the stationary plate is 0.45 m.

Molten steel weighed 200 kg is supplied to the mold from an induction furnace of bottom pouring type with stopper rod, through a tundish, a melt reservoir sealed with argon and an insert-type nozzle. Level of the melt in the mold is controlled by overflowing the melt from the reservoir.

Figure 2 shows the detailed structures of the nozzle and the mold. The nozzle is made of fused-silica and its shape is like a spout. The outer face of the bottom of nozzle and the upper faces of two side walls of the nozzle are respectively pushed onto the lower and upper steel belts, which are along the surfaces of water-cooled copper sleeve rolls. The tip faces of two side walls of the nozzle are also pushed onto the tip

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faces of the stationary copper plates.

These structures, which partly consist of a closed-end mold, seem to make a discontinuous shell growth at the stationary narrow face of the cast. Therefore, it may cause a sticking type breakout.\textsuperscript{10,11}

This is the reason why the inner width of the nozzle is 20 narrower than the distance between two inner surfaces of the stationary plates, in order to make stable casting.

Table 1 shows the casting conditions. Steels of several grades were cast to examine differences in the castability and solidification characteristics.

2. Bend Test of Thin Slab Cast

When a commercial production line is considered, a coil box which is the apparatus for coiling of thin slab should be installed between the thin slab caster and the hot strip mill, in order to match the casting speed with the rolling speed and to eliminate reheating of semis. In coiling practice of thin slab cast, surface cracking may be one of the major problems to be considered. The cracking susceptibility of thin slab has, therefore, been examined by the bend test.

Figure 3 shows the experimental apparatus used for the bend test. The rolling mill is used to transfer thin slab to the bend rollers. Slab samples of several steel grades 2 m long are bent at 1 050°C within 2 to 3 min after being cast. The coiling speed is 15 m/min and the bend radius, \( R \), of the slab is 250 mm.

III. Results of Casting and Bend Test of Thin Slab

1. Surface Quality of Thin Slab

The surface of the thin slab obtained were examined after removal of scale by shot blasting. The wide face is relatively smooth because of the synchronization of belt movement with solidified shell of the wide face.\textsuperscript{7,8} Concave curvatures of about 1 mm depth are observed at the upper and lower surfaces of the wide face, due to the cross bow of belt caused by rolls with small diameter (120 mm) in KCC machine. Concave line denoted by \( B \) in Fig. 4 is observed on the wide surface at a distance, \( \delta' \), from the edge. No particular discontinuity of solidified structure is observed beneath the line. The value of \( \delta' \) is almost the same as the step \( \delta \) indicated in Fig. 2, as

<table>
<thead>
<tr>
<th>Steel grade:</th>
<th>EDDQ, SPCC, SMA50, SUS304, SUS430, 3%Si-steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of thin slab:</td>
<td>30 mm( ^3 \times 100 \text{ mm} )</td>
</tr>
<tr>
<td>Casting speed:</td>
<td>3.8–5.1 m/min</td>
</tr>
<tr>
<td>Superheat in melt reservoir:</td>
<td>20–70°C</td>
</tr>
</tbody>
</table>

shown in Fig. 5.

At the narrow face of the solidified shell, the ripple marks with irregular pitch and cracks between the ripple marks are observed as shown in Figs. 6 and 7, which are similar to the so-called cold shut mark and hot tear crack.\textsuperscript{9} These marks are clear on SUS 304 and not so clear on 3%Si-steel. The pitch of ripple marks varies with the kind of steel.
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Figure 8 shows the change in pitch of ripple mark along casting direction at each narrow face of thin slabs for silicon steel and extra deep drawing steel. This figure shows that pitches of ripple mark of both sides do not agree each other and solidification proceeds independently at the both sides. In KCC machine, the narrow faces of the mold are not moved, that is, the stationary mold, unlike the Hazelett machine. This is supposed to be the reason why the ripple marks are observed on the narrow faces of the slab cast.

Figure 9 shows the relation between the depth of ripple mark and the occurrence frequency of ripple mark \( f_{\text{obs}} \) defined by Eq. (1).

\[
f_{\text{obs}} = \frac{(n-1)}{(p/V)} \quad \ldots \quad \ldots \quad \ldots \quad (1)
\]

where, \( n \): number of ripple marks in the distance \( p \)

\( V_c \): casting speed.

As the occurrence frequency of ripple mark \( f_{\text{obs}} \) becomes high, the depth of ripple mark becomes shallower. This relation is similar to that of the depth
of oscillation mark and the mold frequency in the conventional continuous casting of slab.

2. Solidified Structure

Figure 10 shows the solidified structure beneath the ripple mark with short and long pitch. When the mark pitch is short (11 mm, $f_{obs}=5.8 \text{ s}^{-1}$), discontinuous dendritic structure is not clear. In case of long mark pitch (22 mm, $f_{obs}=2.9 \text{ s}^{-1}$), two kinds of boundary of discontinuous structure are clearly observed, as shown schematically in Fig. 10. It is supposed that the one (b1 in Fig. 10) formed along the slab surface is caused by rapid movement of solidified shell, and the other (b2 in Fig. 10) formed from the surface is caused by flowing of melt onto the solidified surface. These structures are similar to that of nail-like shell beneath the oscillation mark or cold shut beneath the cold shut mark. The discontinuity of solidified structure becomes clear and un-welded part begins to exist along the discontinuous boundary (b2) as the pitch of ripple marks becomes larger, that is, $f_{obs}$ becomes lower as shown in Figs. 11 and 12. The un-welded part is not observed as shown in Figs. 12 and 13, even when the value of $f_{obs}$ is higher than 2.3 $\text{ s}^{-1}$. Figure 13 also shows the relation between the value of $f_{obs}$ and the shell thickness, recognized as the depth of boundary (dotted line) of discontinuous dendritic structure, at the narrow face as shown in Fig. 10. The relations among the depth of un-welded part, the shell thickness and the value of $f_{obs}$ tend to show a good similarity to those among the depth of cold shut crack, the depth of cold shut and the strand withdrawal frequency, in the case of horizontal continuous billet casting. These results indicate that an intermittent solidification and withdrawal of the shell are performed in the stationary part of the mold.

3. Bend Test of Thin Slab Cast

Two types of surface cracks were observed. The one is fine transverse crack whose depth and length are about 1 mm and 1 to 3 mm, respectively. This type of crack occurs on the outer wide face and along the $\gamma$ grain boundaries with sulfur segregation for SS41 and SPCC. The other is corner crack which occurs across the outer corner and along the ripple mark for SS41, SPCC and EDDQ.

For plain carbon steel (C: 0.04 to 0.16 %), the transverse cracking susceptibility of thin slab is considerably influenced by the sulfur content, and is independent of the ratio of Mn/S in the region of 20 to 150. Any crack is not observed when the sulfur content is less than 0.006 %. These results are similar to the behavior of brittleness of continuously cast slab in hot direct rolling.13 The cracks does not occur for stainless steel.

Figure 14 shows the effect of the pitch of ripple marks on the corner cracking susceptibility of thin slab by the bend test. When the pitch of ripple marks exceeds about 40 mm, that is, when the occurrence frequency of ripple mark, $f_{obs}$, is below 1.6 $\text{ s}^{-1}$, corner crack is observed along the ripple mark for both low and middle carbon steels. The value of $f_{obs}$ is nearly the same as the critical value of $f_{obs}$ (2.3 $\text{ s}^{-1}$, Fig. 13) when the un-welded part is formed beneath the ripple mark. Therefore, it is considered that the occurrence of un-welded part causes the occurrence of corner crack along the ripple mark during bending. It is also recognized that the effect of the pitch of ripple marks on the occurrence of hot tear cracks is similar to that of corner cracks.

IV. Solidification Mechanism of Thin Slab in Mold

1. Factors Affecting the Occurrence Frequency of Ripple Mark, $f_{obs}$

As mentioned above, corner crack occurs more frequently during bending of thin slab, as the ripple
mark becomes deeper. It is considered that the occurrence of corner crack can perfectly be prevented by the adoption of such an optimum condition for the structure beneath the ripple mark that the pitch of ripple marks is shorten. Therefore, in order to find the conditions so as to shorten the pitch of ripple marks, the factors affecting $f_{\text{obs}}$ have been examined.

Figures 15 to 17 show the effects of the following casting conditions on $f_{\text{obs}}$.
1) Step, $\delta$, at the connecting part between the nozzle and the stationary mold.
2) Tensile strength, $\sigma_{\text{TS}}$, of a shell at high temperatures.
3) Heat flux, $H_f$, from the stationary mold.

These figures show that low $\delta$, high $\sigma_{\text{TS}}$ and low $H_f$ result in high value of $f_{\text{obs}}$.

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Fig. 11. Effect of the pitch of ripple marks on the solidified structure beneath the ripple mark.

Fig. 12. Un-welded part beneath the ripple mark.

Fig. 13. Effect of the occurrence frequency of ripple mark on the depth of un-welded part and the solidified thickness of the stuck shell.

Fig. 14. Effect of the pitch of ripple marks on the corner cracking susceptibility of thin slab for the bend test.

Steel grade: SPCC

$f_{\text{obs}} = 1.6 \times 10^{-1}$

Casting speed: 3.8 m/min

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2. Solidification Mechanism in Mold

From the results mentioned above, it is considered that the shells solidified on the stationary molds near the nozzle tips move intermittently in spite of continuous movement of the wide faces of the shell. This behavior of the shell at the narrow faces is the same as that in the conventional horizontal continuous casting.

From the consideration, an enlargement of cross section, C–C’, at a solidified shell near the nozzle tip in Fig. 2, is schematically drawn as A–A’ and B–B’ sections in Fig. 18, respectively. In this paper, it was tried to explain the behavior of the narrow face of shell by the use of a model of solidification mechanism as shown in Fig. 19.

It is considered that three kinds of forces are applied to a stuck shell. The first one is the shear force, $F_s$, which occurs between the moving wide faces of shell and the stuck shell. The second one is the friction force, $F_m$, which occurs between the stuck shell and the stationary mold. The third one is the friction force, $F_b$, which occurs between the stuck shell and the moving belts. Here, the following two assumptions are adopted:

![Fig. 15. Effect of the step $\delta$ at the connecting part between the nozzle and the stationary mold on the occurrence frequency of ripple mark.](image)

![Fig. 16. Effect of the tensile strength of cast steel at high temperatures $\sigma_{TS}$ on the pitch of ripple marks.](image)

![Fig. 17. Relation between the heat flux from stationary mold and the pitch of ripple marks.](image)

![Fig. 18. Schematic representation of solidified shell growth at the connecting part between the insert nozzle and the stationary mold at mold inlet.](image)

![Fig. 19. A model of solidification mechanism which explains the intermittent movement of narrow face of shell (A–A’ section in Fig. 18) in mold.](image)
On these assumptions, \( F_s \) seems to increase gradually. The estimated occurrence frequency, \( f_{\text{est}} \), is given by Eq. (2) as a function of \( \sigma \).

\[
f_{\text{est}} = \frac{1}{t_s} = \frac{1}{(\delta/k_s)^2} \]

where \( k_s \) is given as 26 mm/min\(^{-1/2} \) for the copper mold in a horizontal continuous caster. Figure 20 shows the estimated occurrence frequency of ripple mark, \( f_{\text{est}} \), compared with the observed frequency, \( f_{\text{obs}} \). The estimated occurrence frequency, \( f_{\text{est}} \), agrees relatively well with \( f_{\text{obs}} \), although \( f_{\text{est}} \) is less than \( f_{\text{obs}} \). This is considered to be caused by the above two assumptions, which result in an increase in \( t_s \) due to decreases in the withdrawal frictional force, \( F_s \), and \( F_m \), of the stuck shell.

(2) Relations among Tensile Strength, \( \sigma_{\text{TS}} \), Heat Flux, \( H_f \), and \( f_{\text{obs}} \)

It is supposed that the force induced between the moving shell at the wide face and the stuck shell at the narrow face, is regarded as that in the state of tension between the two shells. In this connection, it is considered that an increase in \( \sigma_{\text{TS}} \) results in an increase in \( F_s \). An increase in \( F_m \), therefore, shortens the time, \( t_s \). This evidently makes \( f_{\text{obs}} \) higher, or shortens the pitch of ripple marks.

Furthermore, the low value of \( \sigma_{\text{TS}} \) easily causes bulging of a primary solidified shell, and should result in increases in \( H_f \) and \( F_m \) due to good contact between the stuck shell and the stationary mold. These phenomena are suggested in Fig. 17, that is, \( H_f \) for SUS430 (ferritic austenitic stainless steel) and 3\%Si-steel with low value of \( \sigma_{\text{TS}} \) are comparatively higher than those of the other steels. It is considered, therefore, that \( \sigma_{\text{TS}} \) influences on both values of \( F_s \) and \( F_m \), resulting in the changes in \( f_{\text{obs}} \) and \( H_f \).

Linear thermal expansion coefficient, \( \alpha \), of the shell is also taken into account for the other factor affecting \( f_{\text{obs}} \). Steel with high value of \( \alpha \), or \( \delta-\gamma \) phase transformation such as SUS304 easily forms an air gap, which results in decreases in \( H_f \) and \( F_m \), and hence high value of \( f_{\text{obs}} \) is obtained. Although the value of \( \alpha \) at high temperatures just after solidification is not clear, \( f_{\text{obs}} \) may be influenced by \( \alpha \) in addition to \( \sigma_{\text{TS}} \) and \( \delta \).

From the considerations described above, it is concluded that the experimental results are well explained by the solidification mechanism in KCC mold on the basis of the relation between \( F_m \) and \( F_s \) as shown in Fig. 19.

3. Optimization of Occurrence Frequency of Ripple Mark for Prevention of Corner Crack

From Eq. (2) and Fig. 19, it is suggested the following countermeasures against the occurrence of corner crack of thin slab by increasing the occurrence frequency, \( f_{\text{obs}} \) of ripple mark.

1) The increase in solidification constant, \( k_s \), by intensive cooling of stationary mold.

2) The decrease in step, \( \delta \), at the connecting part between the nozzle and the stationary mold.

3) The decrease in frictional force, \( F_m \), by decreasing the frictional coefficient of the inner surface of the stationary mold.

Under the three optimum casting conditions, the value of \( f_{\text{obs}} \) can be increased to the critical value (2.3 s\(^{-1} \)), and hence the occurrence of corner crack can be prevented.

V. Conclusion

The solidification mechanism of thin slab cast has been investigated by the use of a horizontal twin-belt caster with stationary narrow face of mold and refractory nozzle connecting with the mold in laboratory scale. The cracking susceptibility of thin slab during coiling has also been examined.
The results obtained are summarized as follows:

(1) The ripple marks, similar to the cold shut mark in a conventional horizontal caster, induces the generation of corner crack across the outer corner and along the ripple mark during coiling of thin slab. However, any crack does not occur when the occurrence frequency of ripple mark exceeds 2.3 s⁻¹.

(2) Coiling of thin slab of plain carbon steel causes the occurrence of fine transverse cracks on the outer wide surface and along the γ grain boundary with sulfur segregation. The occurrence of crack can be prevented by decreasing the sulfur content.

(3) Relations among the occurrence frequency of ripple mark, the depth of un-welded part beneath the mark and the thickness of stuck shell are similar to those among the strand withdrawal frequency, the depth of cold shut crack and the depth of cold shut in the conventional horizontal continuous billet casting.

(4) The occurrence frequency of ripple mark depends on the height of step at the connecting part between the nozzle and the stationary mold, and the tensile strength of the solidified shell at high temperatures. These relations can be explained by the proposed solidification mechanism in which the friction force between the stationary mold and the narrow face of shell, and the shear force between the narrow face of shell and the wide face of shell were taken into account.

(5) As a result, it is considered that the solidified shell of thin slab in the mold is formed continuously at the wide faces and intermittently at the narrow faces.

REFERENCES