Improvement of Surface Quality of Continuously Cast Slab for Conditioning-free Rolling*

By Minoru KITAMURA,** Toshiyuki SOEJIMA,** Shinji KOYAMA,** Yoshihiro MATSUDA,** Junji ABU,** Yoshikazu NIMIYA** and Yasutaka YAO**

Synopsis

Refinement in operating practice and technical developments such as degassing, Ar gas shrouding, mould fluxes, tundish refractories, and slab surface temperature control in the secondary cooling zone made it possible to improve the slab surface quality and hence reheat the slab without surface conditioning.

Recently, 80 % of the slabs for plates and 50 % for sheets are charged directly into the reheating furnaces by this process, with excellent results. On the basis of this development, continuous casting of high grade steels such as API-X70 and deep drawable steels have been made possible.

I. Preface

Kakogawa Works, Kobe Steel, Ltd., has made improvements in equipment and operating techniques for its walking-bar type curvilinear continuous slab caster installed in 1973, increasing the capacity from an initial 70 000 t a month to 150 000 t. Also, it has worked on the establishment of techniques for rolling without surface conditioning and hot charging. This paper reports a comprehensive approach to the performance of rolling the slab without surface conditioning.

II. Improved Surface Quality of Plate Steels

Defects observed on the surface of slabs for plate are entrapped scum, longitudinal cracks and fine transverse cracks. Here we describe measures to prevent entrapped scum and longitudinal cracks that are prone to be harmful when rolling without surface conditioning and fine transverse cracks and subsurface cracks that are detrimental to continuous casting of high grade steels such as line pipe.

1. Entrapped Scum

To find the cause of entrapped scum, samples from the surface of slabs were identified and analysed quantitatively by X-ray diffraction. The results showed that the major component was either alumina or zircon type compound and that they are derived from deoxidation products and refractories, respectively.

In an attempt to reduce the occurrence of entrapped scum, the rate of its appearance and the type of mineral components were examined using fluxes with the compositions and properties shown in Table 1. As Fig. 1 shows an obvious correlation is recognized between the quantity of entrapped Al₂O₃ scum and the content of that component in the molten flux. The alumina type scum is considered to be molten slag that was deprived of its fluidity by additional Al₂O₃ floating up in the mould. Therefore, it is desirable that the Al₂O₃ content in the flux should be as small as possible for its increased capacity to absorb Al₂O₃ and that it has a proper consumption rate in order to ensure a reliable slag feed and replace the viscous slag with fresh mould flux. Considering this, type C or type D flux in Table 1 would be effective for preventing alumina scum.

Another important way to prevent Al₂O₃ scums from being entrapped is to prevent effectively primary and secondary oxidation products from entering the mould. Table 2 shows the variation of Al₂O₃ content in molten fluxes in deoxidizing by adding SiC in

<table>
<thead>
<tr>
<th>Kind of flux</th>
<th>Composition (wt%)</th>
<th>CaO/SiO₂</th>
<th>Softening temp. (℃)</th>
<th>Viscosity (poise) at 1 300℃</th>
<th>Complete melting time (sec) at 1 300℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>34.9  31.1  12.0</td>
<td>0.89</td>
<td>1 120  1 160</td>
<td>8.3  20</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>35.5  28.0  14.3</td>
<td>0.79</td>
<td>1 150  1 180</td>
<td>14.4  23</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>36.5  30.3  13.5</td>
<td>0.83</td>
<td>1 150  1 170</td>
<td>11.0  20</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>34.7  27.4  10.8</td>
<td>0.79</td>
<td>1 150  1 160</td>
<td>14.0  14</td>
<td></td>
</tr>
</tbody>
</table>

* Based on the paper published in Tetsu-to-Hagane, 67 (1981), No. 8, Special Issues on Continuous Casting of Steel, 1229, in Japanese. Manuscript received March 9, 1984. © 1984 ISIJ
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the ladle during tapping and by shielding with Ar gas between ladle and tundish, respectively as a countermeasure for the scum. Figure 2 shows the effect of these measures on the amount of entrapped scums produced. As shown, the number of alumina scums was markedly reduced by the added SiC that promoted floating and separation of Al₂O₃ from molten steel and by Ar gas shrouding that prevented oxidation due to air.

Zircon type scums were attributable to the zircon refractories used for the tundish nozzles and stopper heads. At Kakogawa Works, this problem has been solved by changing the quality of these firebricks from the zircon type to the high aluminum type and at the same time changing the flow control method from a stopper to a slide valve.

2. Longitudinal Cracks

Generally speaking, longitudinal cracks in steel occur if flux[1] or mould cooling conditions[2] are inappropriate. Besides, fine cracks caused in the mould may be enlarged by cooling at the secondary cooling zone.

Figure 3 shows the effect of flux viscosity on longitudinal facial cracks. Type B and type D fluxes gave the smallest number of longitudinal cracks.

The performance of the mould fluxes tested is summarized in Fig. 4. Since an obvious correlation was recognized between entrapped scums in slabs and refractory inclusion marks in plate and between longitudinal facial cracks in slabs and scabs and longitudinal flaws in plates, Kakogawa Works adopted type D flux that produced the least amount of entrapped scums and longitudinal cracks in slabs. It has helped to produce slabs with good surface quality.

3. Fine Transverse Cracks and Subsurface Cracks

Fine cracks in the slab surface, which are commonly observed in Al killed steels and Nb containing steels, increase the amount of scarfing and sometimes cause serious facial defects in the final product. These cracks are great obstructions against extending the continuous casting method for other kinds of steels.

These cracks in the slab surface, generally called transverse cracks,[3–6] can be classified into two groups according to how they take place. One type is cracks that occur only on the loose side surface of slabs produced by curved continuous casting machines (hereinafter called fine transverse cracks), and the other is those that occur in the about 30 mm thick slabs.

### Table 2. Effect of SiC deoxidation and Ar sealing on Al₂O₃ content in melted flux for 40 kg/mm² class steels.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>SiC deoxidation</th>
<th>Ar seal of casting stream between ladle and tundish</th>
<th>Al₂O₃ content in melted flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Number of data</td>
<td>Average (%)</td>
</tr>
<tr>
<td>I</td>
<td>No</td>
<td>No</td>
<td>15</td>
</tr>
<tr>
<td>II</td>
<td>Yes</td>
<td>No</td>
<td>13</td>
</tr>
<tr>
<td>III</td>
<td>Yes</td>
<td>Yes</td>
<td>19</td>
</tr>
</tbody>
</table>

![Fig. 2. Effect of SiC deoxidation and Ar seal on entrapped scums.](image)

![Fig. 3. Relation between longitudinal facial crack and viscosity of flux.](image)

![Fig. 4. Relation between index of conditioning of plate and kind of flux.](image)
subsurface layer of the fixed side as well as the loose side of the slab (subsurface cracks).

1. Fine Transverse Cracks

The relation between secondary cooling patterns and surface temperatures of slabs is shown in Fig. 5 during the casting of API-X70. In pattern A, where the temperature did not rise again in the slab straightening zone, no small lateral cracks were found, while in pattern B, where the temperature rose again in that region, some were observed. Figure 6 shows the relation between temperature at the secondary cooling zone outlet and fine transverse cracks when the quantity of cooling water was changed in pattern A; very few cracks were found between 800 °C and 920 °C at the secondary cooling zone outlet corresponding to the end point of steel straightening.

The above results show that to prevent fine transverse cracks one should first prevent the temperature from rising again in the secondary cooling zone (that is to say straightening region). As pointed out by other papers, too, the cycle of cooling and heating produces thermal stresses that have something to do with fine transverse cracks along with stresses due to straightening, and the process of temperature rising again accelerates precipitation of AlN of Nb (C, N) and makes cast slabs substantially brittle. However, even if the temperature in the straightening zone is prevented from rising again, fine transverse cracks are existent if the slab surface temperature drops below 800 °C. One reason for this phenomenon would be that below 800 °C pro-eutectoid ferrite particles precipitate in austenite grain boundaries and the straightening is done under the two-phase condition and this in turn causes stress to be concentrated in the phase-to-phase interface, a condition where cracks are apt to occur. Another reason might be that the ferrite precipitate promotes the precipitation of AlN or Nb (C, N) and makes cast slabs brittle. From this, it is thought that to prevent fine transverse cracks, straightening in one-phase region, of austenite is more effective. Under this condition, however, if the temperature is too high (over 920 °C in the case of this report), fine transverse cracks will be observed again. This will be because excessively high temperatures at the straightening zone make austenite grains coarser and make the area of grain boundaries relatively smaller. This role of grain boundaries is thought to absorb straightening strains.

2. Subsurface Cracks

Photograph 1 shows the macrostructure of a slab in which subsurface cracks are observed. This kind of macrostructure is seen in slab that is cooled quickly to below the transformation temperature of Ar3 and allowed to be heated again. The cracks are observed in the subsurface of loose side and of fixed side. A super cooled macrostructure marking is always noted to remain without being subjected to macro-etching on the surface side of the region where cracks are caused.

Photograph 2 shows the microstructure in the vicinity of subsurface cracks. The microstructure varies from the surface to the interior, and this shows that each part underwent different hysteresis of transformation. To understand at what temperature these structural changes are caused, a transformation test was made by cooling test pieces of 15 mm in diameter and 55 mm in length using Formastor from 1300 °C in various temperature patterns. The re-
results and the cooling patterns used are shown in Photo. 3 and Fig. 7, respectively. The photograph reveals that the bainitic structure in the macro pattern was formed as a result of a bainitic transformation due to heavy cooling at the spray zone and of the subsequent temperature re-rise to just above $A_s$ and that the fine ferrite-pearlite structure in the exterior side of the macro pattern is due to the process of cooling and temperature re-rise in the $A_s$ to $A_f$ range by intermittent spraying of water. Also, the coarse ferrite-pearlite structure in the interior of the marking might remain in the austenite phase without being transformed in the spray zone and then be slowly cooled. Thus, when over-cooling reheating of the skin of the slabs occurred, excessive thermal and/or transformational stresses might lead to subsurface cracking due to change in volume during phase transformation.

According to the test results, the stresses responsible for subsurface cracks are thermal and transformational. In addition, slabs weakened by coarse crystal grains, $A_1N$ precipitates, ferrite locally precipitating into austenite grain boundaries have great effects on subsurface cracks.

3. Countermeasures against Fine Transversal Cracks and Subsurface Cracks

In view of the results of our tests and observations for casting Nb containing steels (typical application API-X70) and aluminum killed fine grain steels, it is required to use a secondary cooling pattern like Fig. 5(A) that will restrict the extent to which the surface temperature of slab rises again at the cooling zone and after it. At Kakogawa Works, the temperature immediately after the cooling zone has been selected in the 850 to 950 °C range to prevent almost entirely these two types of cracks.

### III. Improved Surface Quality of Low-carbon Aluminum Killed Steel for Sheet

Law-carbon aluminum killed steel, the major steel grade for sheet, is subject to virtually no cracks at the slab level because of its low sensitivity to cracks. Nonetheless, some problems in this steel are entrapped scums attributable to deoxidation products, secondary oxidation and deteriorated fluxes and alumina clusters in the surface layer of a slab.9,10 Below are described how these problems are influenced by various conditions at the following three points, and how they can be prevented.

1. The process of blowing at converter and Ar bubbling,
2. Between ladle and tundish, and
3. Between tundish and mould.

#### 1. Process of Blowing at Converter and Ar Bubbling

For low-carbon aluminum killed steels, molten metal is blown down to a low-carbon region. Because of this, the slag becomes higher in iron oxide ($T. Fe$) content and more fluid and thus is apt to flow out into the ladle at the time of tapping. This slag and air oxidizes Al in the molten metal, forming $Al_2O_3$ that is a cause of entrapped scums and alumina clusters.

Table 3 is an example of changes in the content of $Al_2O_3$ and $T. Fe$ in the slag in the ladle from tapping to Ar bubbling, together with that of the material balance of Al charged as the deoxidizing agent. Of the added Al, 34 and 19 % were oxidized by the air and the $T. Fe$ in the slag, respectively, during tapping and Ar bubbling. Most of the $Al_2O_3$ particles produced during secondary oxidation is separated from the molten steel and floats up during Ar bubbling, but part of it remains in the molten metal and is brought into the mould. Figure 8 shows a relation between the $T. Fe$ content in converter slag and the number of entrapped scums in the slab. From this, it is seen that the higher the content of $T. Fe$, the more conspicuous entrapped scums will be and that the effect of secondary oxidation cannot be ignored.
At Kakogawa Works, considering these results, entrapped scums have been prevented by such measures as control of the upper limit of T.Fe content, reducing the slag volume at the time of tapping, and RH degassing.

2. Between Ladle and Tundish

In the continuous casting process between ladle and tundish, the flow of molten metal poured is subject to oxidation by the air and there is an increase of Al₂O₃. Figure 9 shows how many alumina clusters were reduced below the slab skin when the flow of molten metal poured was shielded by Ar gas to prevent oxidation. The figure shows that alumina clusters are considerably diminished in Ar shielded materials but conspicuous in those not shrouded. Figure 10 exhibits casting set-up with Ar shrouding. Figure 11 shows the relation that differences (ΔAl) in the Al content between molten metal in the ladle and molten metal in the mould bear to the amount of alumina clusters below the slab skin. A strong correlation was recognized between the two and this shows that if the amount of alumina clusters is to be lowered, it is very important to prevent oxidation by air between ladle and tundish.

Figures 9 and 11 also compare the results of two methods of cleaning molten steel; Ar bubbling and vacuum degassing. They both show that the de-
gassing method produced fewer alumina clusters in slab. The reason is that the degassing method is more effective for deoxidation and that being performed in a vacuum and small in both inclusion quantity and size.

3. Between Tundish and Mould

It is essential that when brought into the tundish, as many Al₂O₃ inclusions as possible should float up and that the molten metal should be protected from contamination by the tundish refractory. Therefore, effective measures against entrapped scums here are to use the tundish weir with a gate of optimum shape, to blow a small amount of Ar gas from the tundish nozzles, and to select the appropriate refractory material.

As an example of the effects of these measures, Fig. 12 compares the amount of Al₂O₃ inclusions in slab when RH degassed molten steel was cast in three different ways.

Material A—A tundish made in part from SiC-SiO₂ type refractory and a weir of pyrophyllite were used.

Material B—The same refractory as for material A was used with longer degassing process.

Material C—High alumina refractory was used for the tundish and weir, and Ar gas was blown from the tundish nozzles.

As compared to materials A and B, material C is shown to be so improved that the amount of alumina clusters under the skin has been stabilized below the critical range to accomplish rolling slabs without surface conditioning.

4. Slab Quality and Finished Product Quality

Figure 13 shows a relation between the T.Fe content in slag at blow-end of the converter and sliver defects in cold rolled steel, and Fig. 14 shows that of ∆Al and sliver defects in cold rolled steel. A correlation was noted between each of these two groups of parameters, and it was found that T.Fe and ∆Al could serve as indicators for control of the manufacturing process.

In order to examine the effect of the amount of alumina clusters under the skin of slab on the formation of sliver defects, slabs from nine heats of the type shown in Fig. 9 were tested for sliver defects produced by different amounts of scarfing. As a result, it was found that if the alumina clusters occupied not more than 0.02 to 0.03 % of the area under the skin, no sliver defects were formed whether the slabs were scarfed or not. Therefore, at the Kakogawa Works, by refinements mentioned above in Sec. III. 1 and 2, low carbon aluminum killed steels are cast so successfully that large globular inclusions are greatly reduced in the slab surface.

IV. Rolling Slabs without Surface Conditioning

In addition to the improved manufacturing techniques from blowing converter through other continuous casting operations outlined in the foregoing by which slabs in general are made, the following method is used to determine the surface quality of plates: the slab at the bottom is sampled from No. 1 heat and thereafter one slab each from every five
heats, and they are scarfed to check if they are acceptable for rolling without surface conditioning. With slabs for sheet, in order to determine the surface quality, TFe in the slag produced due to blowing in the converter and ΔAl, shown in Chapter III, are used as control indicators, and based on them, it is determined whether rolling without surface conditioning is possible or not. At present, about 80% of the slabs for plates and about 50% of those for sheet are rolled without surface conditioning at the Kakogawa Works.

For more energy conservation, hot charging into the furnace of hot rolling mills was started in the beginning of 1979. At the time of this report, about 30,000 t a month for plates and sheets are being hot charged. Moreover, improved surface quality of continuous cast slabs has also made it possible to cast in this way high grade steels such as grade X70 steel for line pipe, deep drawing steels, and steels for automobile frames.

V. Afterword

The surface properties of steel plates rolled without surface conditioning have been made better than those rolled by conventional methods owing to improved operating techniques and the establishment of systems for checking the manufacturing process and inspecting the surface quality of slabs. The challenges yet to be met are:

- to expand the types of steels that can be rolled without surface conditioning, and
- to better match casting production schedules and subsequent processes, increasing the amount of hot charged materials.

REFERENCES