Qualities of Billets Produced by Continuous Casting with In-line Reduction*

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Synopsis
Billet continuous casting machine with in-line reduction, was installed at Kishiwada Steel Co., Ltd., and has been in operation since March 1972. This paper deals with various qualities of billets produced by this machine during the start up period.

The followings have been found:
(1) Center shrinkage cavities and porosities were well cured by the in-line reduction process.
(2) The non-metallic inclusions were elongated into the drawing direction throughout a billet by the in-line reduction process, however the inclusions locating at central parts extended further than those at outer layers.
(3) Microscopic examinations yielded that as-cast billets consist of normal Widmannstätten structures but the in-line reduction improves the structure to some extent.
(4) Difference of the tensile properties between the central part and the outer layer of billet was negligible.

Consequently it is concluded that the in-line reduction process results in excellent qualities and soundness to billets.

I. Introduction

Though there have been a number of publications on the qualities of continuous casting billets, only few investigations were made on billets produced by an in-line reduction which reduces the billet size while being drawn from a mould before cutting into a regular dimension.

Tarmann1) and other authors2,3) reported improved qualities of billets through the in-line reduction processing, however detailed examinations on the reduction effect at various locations of the processed billets are yet to be made.

In this paper, mechanical and metallurgical uniformity induced by the in-line reduction is dealt with for billets processed by a powder-cast continuous casting machine with the in-line reduction during the start up period. The machine was installed at Kishiwada Steel Co. Ltd., and has been in operation since March 1972. The billets with the initial cross section area of 140 x 140 mm are treated through a two step reduction processing reducing the area down to 105 x 140 mm in the first and to 105 x 105 mm in the final stage. Table 1 shows the important specifications of this machine.

II. Experimental

Before we go into details of experimental procedures, a number of terminologies used in this paper are defined for the sake of simplicity.

An inner surface: a billet surface which makes a contact with the inner roll upon drawing.

An outer surface: a billet surface which makes a contact with the outer roll upon drawing.

A transverse cross section: a billet cross section perpendicular to the drawing direction.

A longitudinal cross section: a billet cross section containing the center axis of the billet and perpendicular to the inner and outer surface.

Existence of cracks on the billet surface was examined by eye-inspections while internal qualities were observed applying macro-etching to a longitudinal and a transverse cross section of a billet with an etchant of 1:1 HCl solution at 70°~75°C for 20 min.

Cleanliness, size and shape of inclusions were checked throughout a whole area of a longitudinal cross section. The JIS G 0555 method (microscopic examination of non-metallic inclusions in steel) was employed for cleanliness measurement which was carried out at a number of points starting from 5 mm depth from the inner surface toward the outer surface with 10 mm interval. 60 views were examined at the surroundings of each point. The same method was applied for the measurement of inclusion size except with spots of 2 mm interval starting from 2 mm depth from the inner surface. However in this case the microscope stage was moved about 10 mm parallel to the inner surface at each measuring point and the maximum inclusion size found in the area was measured. The inclusion sizes were expressed in terms of circular diameters while for oval inclusions, calculated diameters of spheres with areas equivalent to the ovals were taken into the considerations. The positional change of the inclusion shape was observed along a horizontal array of spots with an interval 5 mm from the inner surface to the outer surface. The stage was moved about 30 mm vertically at each spot and axial ratio of the maximum inclusion found in the area were plotted.

Microstructures were also investigated before and

Table 1. Details of machine

<table>
<thead>
<tr>
<th>Machine type</th>
<th>Straight mold bending type with in-line reduction stand</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of strand</td>
<td>2 strands</td>
</tr>
<tr>
<td>Ladle capacity</td>
<td>40 t/charge</td>
</tr>
<tr>
<td>As cast billet size</td>
<td>140 x 140 mm</td>
</tr>
<tr>
<td>Final billet size</td>
<td>105 x 105 mm</td>
</tr>
<tr>
<td>Billet length</td>
<td>1 800 - 2 000 mm</td>
</tr>
<tr>
<td>Casting speed</td>
<td>2.4 m/min</td>
</tr>
<tr>
<td>Steel grade</td>
<td>Steel bar for concrete reinforcement</td>
</tr>
<tr>
<td>Bending radius</td>
<td>5 000 mm</td>
</tr>
<tr>
<td>Casting method</td>
<td>Submerged nozzle and powder casting</td>
</tr>
</tbody>
</table>

* Received June 14, 1974.
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after the reduction processing for the same samples used for the inclusion size measurement.

As for the homogeneity of mechanical properties, tensile specimens (JIS 4 type) with stress axis parallel to the drawing direction were taken from the center and the near surface parts of the processed billets. The tests were conducted after annealing the specimens at 950°C. Since billets before the in-line reduction contain a number of shrinkages and porosities at the center parts and thus poor elongation and reduction of area are anticipated, the mechanical tests for these billets were not conducted. Table 2 summarizes the chemical composition of billets, casting conditions, and test items conducted in the present investigation.

III. Results and Discussions

1. Surface Qualities

Surface qualities were affected by chemical composition, casting temperature, casting speed, cooling ability of secondary water line, absolute surface temperature and its distribution on billet surfaces. Though the casting temperature and the secondary cooling water rate have to be controlled, we found that the surface temperature homogeneity is most influential for the in-line reduction processing. In the present machine, a temperature homogenizing tunnel was installed just before the reduction stand in order to establish a desirable temperature homogeneity and excellent surface qualities of the products. Photographs 1 (a) and (b) show representative surface appearances and soundness of surfaces obtained for a billet produced by this machine.

2. Macrostructures

Photograph 2 illustrates the macro etched transverse and longitudinal sections of a billet before (left) and after (right) the reduction processing. Because of relatively high temperatures anticipated at the center part of as-cast billets, the in-line reduction works very effectively to cure center shrinkages.

3. Inclusions

The local variation of the cleanliness in a number of billets produced from raw materials with different sulphur contents was plotted in Fig. 1. Despite of the wide fluctuation, it can be said, generally speaking, that the surface layers are relatively clean but cleanliness declines considerably as it goes to the center. The results does not coincide with the observations of other reporter.4) The effect of sulphur contents on the cleanliness can be well expressed as the average cleanliness for each billets in Fig. 1, and is plotted against sulphur contents in Fig. 2 which shows increasing A type inclusions with increasing sulphur contents while virtually no change in C type inclusion density is seen.

EPMA analysis yielded that A type inclusions are mostly sulfides and no silicates are found as shown in Photo. 3. The observation that sulfides inclusions increase as sulphur content increase well corresponds to the other result.5)

The positional variation of inclusion size is seen in Fig. 3 for four billets with different sulphur content. In each diagram, corresponding crystalline structures observed by the macro-etching are indicated as well. Smaller inclusions are found at the surface layers, but the size increases at the center parts and particularly for a high sulphur billets, a broad distribution is seen.

In the columnar crystal zone, the size increases at the center, and in the equiaxed crystal zone, the size

![Photo 1. Surface appearance of continuously cast billet](image)

<table>
<thead>
<tr>
<th>Heat No.</th>
<th>Chemical Composition (%)</th>
<th>Casting TEMP. (°C)</th>
<th>Casting speed (m/min)</th>
<th>Cooling water (1/kg)*</th>
<th>Test Item**</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>0.25 0.40 0.77 0.020 0.029 0.007</td>
<td>1555</td>
<td>2.40</td>
<td>0.97</td>
<td>Inclusion test I</td>
</tr>
<tr>
<td>243</td>
<td>0.26 0.40 0.85 0.020 0.029</td>
<td>1565</td>
<td>2.20</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>234</td>
<td>0.28 0.35 0.74 0.023 0.015 0.005</td>
<td>1550</td>
<td>2.40</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>235</td>
<td>0.26 0.24 0.75 0.024 0.012 0.006</td>
<td>1545</td>
<td>2.40</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>233</td>
<td>0.25 0.39 0.86 0.020 0.009 0.006</td>
<td>1555</td>
<td>2.40</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>238</td>
<td>0.23 0.25 0.82 0.021 0.004</td>
<td>1575</td>
<td>2.25</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>3525</td>
<td>0.21 0.26 0.83 0.024 0.015</td>
<td>1565</td>
<td>2.45</td>
<td>0.93</td>
<td></td>
</tr>
</tbody>
</table>

* The value is for secondary cooling water.
** I...Cleanliness; II...Size; III...Shape

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fluctuates considerably with high sulphur contents while it is rather constant with lower sulphur contents. As shown in Photos. 4 (a) and (b), the large inclusions are A type while small ones are mostly C type inclusions with less than 5 μ diameter. This well corresponds to the other investigation. The observed inclusion size dependence on the crystalline structures is considered to be caused by difference in molten temperature and fluidity as a billet solidifies. Namely with high molten temperature and fluidity at the period of the gradual progression of columnar grain growth, there is sufficient times and temperature for
inclusions to condense and grow while relatively low temperature and fluidity at equiaxed crystal zone motivate simultaneous solidification of each crystal inducing a wide variety of inclusion sizes.

As we summarize the morphology of the sulphide inclusions using a shape index expressing a ratio be-
between major and minor axial length in Fig. 4, it is observed that the inclusions near surface layer are observed to be fairly circular with the index of 1~1.5 against ~3 for the ones in the central region of a billet before reduction processing (a). In a reduction processed billet (b), the index goes up to 2~3 at the surface layer while 6~10 is measured for the center parts. The observations above strongly indicate the effectiveness of the reduction on the inclusion shape. Photographs 5 (a) and (b) show the representative inclusion morphology before and after the reduction, respectively. Thus it is concluded that the reduction processing works more effectively at the center part than at the surface layers. The tendency may be expressed with a positional variation of a reduction ratio which is defined by

\[
\text{reduction ratio} = \frac{\text{shape index after reduction}}{\text{shape index before reduction}}
\]

The reduction ratio at various positions of a billet is illustrated in Fig. 5 which indicates a strong reduction effect at the center where the reduction ratio is above 3. This is very remarkable because the billet size was reduced from 140 mm to 105 mm and thus as a whole the billet received only 1.8 reduction.

4. **Microstructures**

The reduction effect on the metallurgical structures can be seen in Photo. 6 which illustrates microstructures of various parts of billet before (left) and after (right) the processing. The structures are generally improved with fewer Widmannstätten phase by the reduction. The effect appears to be significant at the region between the surface and the center, but successive heat treatments of annealing or normalizing is considered to be still necessary in order to attain acceptable states as shown in Photo. 7.

![Fig. 4. Shape index change of billet before and after reduction](image)

![Fig. 5. Local variation of reduction ratio of billet](image)

![Near inner surface](image) ![Center](image)

*Photo. 5. Inclusion of billet before and after reduction*
Before reduction

After reduction

Near inner surface

Intermediate

Center

Photo. 6. Microstructure of billet before and after reduction

Fig. 6. Mechanical properties of continuously cast billet (105 mmφ)

Photograph 8 shows an example of an sufficiently improved structures by an in-line reduction from 140 mmφ to 80 mmφ reported by other authors.\(^7\)

5. Mechanical Properties

It has been reported\(^4\) that difference of mechanical properties especially elongation and reduction of area between surface layers and center parts of a continuous cast billet diminishes at the reduction ratio 10. However as seen in Fig. 6, negligible difference was found for tensile strength, yield point, elongation, and reduction of area between the surface and the center part. A better reduction effect is also seen at the center parts despite of the small reduction ratio of 1.8.

These observation can be confirmed by the change in macrostructure and inclusion shape through the reduction.

IV. Conclusions

1. The in-line reduction processing delivers ex-
cellent internal qualities with well cured center shrinkages and porosities.

(2) The reduction works effectively at the center portion of billet where the inclusions are more elongated than at the surface layers.

(3) Number of sulfide inclusions increases as sulfur content increases while no dependence is found for oxide inclusions.

(4) Difference of the tensile properties between the central part and the outer layer of billet after reduction is negligible.

(5) A broad variety of inclusion sizes are observed for sulfide inclusions but most oxides are measured to be below 5 μ. Especially in a high sulfur steel, large inclusions are found at the center of a billet.

REFERENCES

7) B. Tarmann: Report from the Böhler Engineering Division, Kapfenberg, Austria (1971), 17.

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