Advances in Stainless Steelmaking Technology

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Abstract:
A high-speed and high-efficiency decarburization technology was established for the manufacture of austenitic stainless steel at Hikari Works. This technology improves the efficiency of decarburization efficiency and shortens the refining time by the AOD combined blowing whereby the effect of the hot spot formed by hard-blown top oxygen is fully utilized. At Yawata Works, on the other hand, decarburization technology was established for the manufacture of ferritic stainless steel. It achieves optimum load distribution between LD converter with high carbon turndown and VOD with high-speed decarburization by vacuum control to prevent bumping and by intense stirring with increased ladle bottom injection argon. A new decarburization index S-BOC indicating the oxidation of carbon in preference to chromium is proposed to explain the effect of combined blowing. The world’s first technology of manufacturing metal catalyst carrier through continuous casting was established by developing an optimum mold powder and an appropriate technique for high-precision addition of REM into the mold.

1. Introduction
In a nearly one century since the birth of stainless steels around 19101, stainless steelmaking technology has made outstanding progress, and various new processes have been employed in combination in the commercial production of stainless steels2. This article reviews the history of technology development for the manufacture of austenitic and ferritic stainless steels. Of the recent stainless steelmaking technologies, combined blowing with argon oxygen decarburization (AOD), dephosphorization of high-chromium hot metal, high-efficiency and high-purity steel production with vacuum oxygen decarburization (VOD), and metal catalyst carrier production are described.
Table 1 shows the changes in austenitic and ferritic stainless steelmaking technologies at Nippon Steel.

2. Austenitic Stainless Steelmaking Technology
Nippon Steel produces austenitic stainless steels represented by SUS 304 at its Hikari Works. The stainless steelmaking process comprises 60tons/heat electric arc furnace (EAF), AOD, and continuous caster (CC) steps. In the EAF step, stainless steel scrap and ferroalloys, such as ferrosilicon and ferronickel, are preheated by kerosene burners and melted by alternating-current (AC) arc in a new melting furnace (NMF)3 of the one-power supply, two-
### Table 1 Changes in stainless steelmaking technologies at Nippon Steel

<table>
<thead>
<tr>
<th>Year</th>
<th>Hikari Works</th>
<th>Yawata Works</th>
<th>Muroran Works</th>
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<tbody>
<tr>
<td>1951</td>
<td>Stainless steelmaking test started with 304 EAF</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking started with 50 t test furnace</td>
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<tr>
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<td>10-4 EAF started up (operated until 1979)</td>
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<td>Stainless steelmaking started with 50 t test furnace</td>
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<tr>
<td>1961</td>
<td>40-4 EAF started up (operated until 1986)</td>
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<tr>
<td>1963</td>
<td>Vertical slab caster started up (single-strand)</td>
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<td>Stainless steelmaking started with 50 t test furnace</td>
</tr>
<tr>
<td>1966</td>
<td>40-4 DH started up (operated until 1974)</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking started with 50 t test furnace</td>
</tr>
<tr>
<td>1967</td>
<td>Vertical slab caster started up (single-strand)</td>
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<tr>
<td>1968</td>
<td>40-4 EAF started up (operated until 1986)</td>
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<td>1969</td>
<td>Vertical slab caster started up (single-strand)</td>
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<td>Stainless steelmaking test started with 220 t furnace</td>
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<td>1983</td>
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<td>1986</td>
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<td>1988</td>
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<td>Stainless steelmaking test started with 220 t furnace</td>
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<td>1990</td>
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<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking started with 50 t test furnace</td>
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<tr>
<td>1991</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking started with 50 t test furnace</td>
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<tr>
<td>1992</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking test started with 220 t furnace</td>
<td>Stainless steelmaking started with 50 t test furnace</td>
</tr>
</tbody>
</table>

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The table above shows the changes in stainless steelmaking technologies at Nippon Steel from 1951 to 1992. Each entry represents a significant technological advancement in the steelmaking process, such as the introduction of new furnace types or improved casting methods.

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After decarburization and slag reduction (desulfurization) in the AOD furnace, the steel is taphed into a ladle. In the ladle, the melt is stirred by argon bubbling for temperature and chemistry homogenization before being totally fed into the continuous caster. There are three continuous casters: a vertical slab caster, a vertical bloom caster, and a horizontal bloom caster.

Regarding the AOD refining technology, various development and commercialization results have been achieved to date with the aim of raising productivity and improving product quality. Among them are optimization of the oxygen-argon blowing pattern according to specific carbon content requirement (AOD-O process)\(^5\), reduction in sulfur and oxygen contents to ultralow levels through aluminum addition and slag composition control\(^6\), and improvement in refractory quality. A 2-10 ton combination vacuum induction melting (VIM) furnace was installed for small-lot production of high-alloy steel with high purity, utilizing flux refining\(^7\).

### 2.1 AOD Combined Blowing Technology

AOD combined blowing (top and bottom blowing) is being introduced to increase the total oxygen flow rate and thermal feasibility by adding top blowing\(^8\). The conventional top blowing process performed soft blowing with a bath surface depression ratio \(L/L_0\) of 0.05 or less (where \(L\) is the bath surface depression depth caused by top blowing and \(L_0\) is the static bath depth). This soft blowing was designed to promote post-combustion, increase the heating rate of the molten steel, and suppress the oxidation of chromium\(^9,10\). The decarburization rate is thus considered to be lower than in bottom blowing at the same oxygen flow rate. Work was started on the development of efficient combined blowing technology. Preliminary experiments were conducted with a 100-kg furnace and a 6-ton combined-blown converter. The experimental results obtained were applied to the actual process to improve the decarburization rate and efficiency at the same oxygen flow rate as in bottom blowing.

#### 2.1.1 Analysis of Top-Blown Hot Spot Reaction by 100-kg Furnace Experiment

Fig. 1 shows the effects of top blowing, bottom blowing, and combined blowing on the relationship between the carbon concentration and the decarburization rate at the same oxygen flow rate of 100 Nl/min in the 100-kg furnace. Top blowing was kept on the hard blow side at \(L/L_0 = 0.1\) to promote the reaction of top-blown oxygen with the steel bath. For combined blowing, the ratio of top-blown to bottom-blown oxygen was set at 1:1. The solid marks in Fig. 1 indicate the region where chromium is oxidized and the slag is increased in \(Cr_2O_3\) content and solidified. Judgment of slag solidification was made from video images during the blowing.

The decarburization rate improves from top blowing, bottom blowing to combined blowing in that order. The same order holds for the decrease of the carbon concentration at which the decarburization rate drops and slag solidifies. Video images showed
that the bath surface was covered with slag solidified by the formation of Cr$_2$O$_3$, which prevented the top-blown oxygen from reaching the molten steel thereby to retard the oxygen-steel reaction. Analysis of hot spot spectra by two-color radiation thermometry confirmed that the top-blown hot spot temperature was a high 2,350°C on the average for both top blowing and combined blowing. The molten steel in the bath surface near the top-blown hot spot was sampled using a copper lump (50 mm in diameter). The sample was sectioned and examined by an optical microscope and electron-probe microanalyzer (EPMA). Chromium oxides were identified on the sample cross section. This result confirmed that the hot spot has a high temperature and forms a high-oxygen region (chromium oxide layer), and that the oxygen concentration (chromium oxide layer) is reduced more drastically in combined blowing than in top blowing. It was thus found that combined blowing promotes the Cr$_2$O$_3$ reduction reaction at the high-temperature hot spot and that intense bottom-blown gas stirring accelerates the decarburization of the melt by promoting the transfer of oxygen from the hot spot.

\[(\text{Cr}_2\text{O}_3) + 3\text{C} = 2\text{Cr} + 3\text{CO}(g) \]  

(1)

2.1.2 Determination of optimum top blown-to-bottom blown oxygen ratio by 6-ton converter test; proposal of new refining index

Fig. 2 shows the effect of the top-blown oxygen ratio (= top-blown oxygen/total blown oxygen) on the average decarburization rate at and above the carbon concentration of 0.5 mass% in the 6-ton combined-blown converter test. Each top blowing run was hard blowing with $L_1/L_0 = 0.1$. As the 100-kg furnace test did, the 6-ton furnace test confirmed that combined blowing can improve the decarburization rate compared with bottom blowing, and verified the existence of an optimum top-blown oxygen ratio for the decarburization rate. Fig. 3 shows the effect of the molten steel stirring energy $\dot{e}$ on the average decarburization rate. The stirring energy $\dot{e}$ was calculated from the equation of Kai et al.\cite{13} taking into consideration the stirring force of top-blown oxygen as well. The stirring energy $\dot{e}$ being equal, combined blowing marks a higher decarburization rate than top blowing. Under combined blowing, the decarburization rate comes to a saturation point when the stirring energy $\dot{e}$ exceeds 6 kW/t, as is separately confirmed by the results of the 100-kg furnace test. This points to the importance of promoting decarburization by Cr$_2$O$_3$ at the top-blown hot spot when stirring is intense at 6 kW/t or over.

According to the above test results, a preferential decarburization index that indicates the oxidation of carbon in preference to chromium was studied. BOC\cite{10}, ISCO\cite{11}, and CROI\cite{12} have been applied to stainless steel for its similarity to plain carbon steel. These indices do not take into account the temperature of the heat that has a large impact on the decarburization of stainless steel and the top blown hot spot reaction that is essential for combined blowing. It was found that they could not uniformly express the decarburization performance of bottom blowing, top blowing and combined blowing as exhibited in the results of the 100-kg and 6-ton furnace tests.

The decarburization of stainless steel depends on the balance between the oxidation and reduction of chromium. Assuming that the transfer of carbon to the reaction interface depends on the mixing time ($\tau$) and interfacial carbon concentration ([%C]*), the reduction of chromium is expressed by \((1/\tau)\cdot([\%C] - [\%C]*)\). Assuming that the oxidation of chromium depends on the oxygen flow rate and slag volume per unit weight of molten steel, it is expressed by \((Q_{02}/W)\cdot W_r\). As a new preferential decarburization index for stainless steel, S-BOC is defined as given by

\[S-\text{BOC} = \frac{Q_{02}}{(W/\tau) \cdot ([\%C] - [\%C]*)} \cdot \frac{W_r}{(1 - ([\%C]/([\%C])))} \]  

(2)

where $Q_{02}$ is total oxygen flow rate (Nm$^3$/min); W is weight of molten steel (t); $W_r$ is weight of slag per unit weight of molten steel (kg/t). Equation (2) can be finally reduced to Eq. (3) by assuming the following conditions: 1) the carbon and chromium
concentrations are constant; 2) the mixing time \( \tau \) is expressed as \( \tau \propto W^{2/3} \gamma^{-1/3} \) under intense stirring; 3) the reaction rate is controlled by mass transfer; 4) combined blowing is the sum of top blowing and bottom blowing; and 5) the CO partial pressure \( P_{CO} \) is expressed as \( 2Q_{O_2}/(2Q_{O_2} + Q_d) \).

\[
S\text{-BOC}=\frac{[\% C]_B}{[\% C]_A} \cdot \frac{W_{BO}}{W_{AO}} \cdot \frac{2Q_{O_2}}{2Q_{O_2}+Q_d} \cdot \left[ \frac{1}{\epsilon} - \frac{Q_{O_2}}{C_1T} + \frac{Q_{O_2}}{C_2T} \right]
\]

where \( \epsilon \) is stirring energy density (kW/m³); \( Q_d \) is inert gas flow rate (Nm³/min); \( K_1 \) is \( 10^{-13800/T_1+8.76} \) [where \( T_1 \) is steel bath temperature (K)]; \( K_2 \) is \( 10^{-13800/T_2+8.76} \) [where \( T_2 \) is hot spot temperature (K)]; \( C_1, C_2 \) are coefficients related to top blowing conditions; subscript B is bottom blowing; and subscript AO is top blowing. Equation (3) consists of: 1) [C] and [Cr] concentration terms; 2) slag and steel weight terms; 3) \( P_{CO} \) term; 4) stirring energy term; and 5) temperature term. Each of \( C_1 \) and \( C_2 \) is a function of the both the temperature and area of the top-blown hot spot. They were determined from the results of the 6-ton furnace test.

Fig. 4 shows the 100-kg and 6-ton furnace test data and actual operation data as arranged by the S-BOC index. The S-BOC index can uniformly express both bottom blowing and combined blowing. Decarburization at the high-temperature top-blown hot spot should improve the decarburization efficiency under combined blowing. This index also suggests that the decarburization of the heat can be accelerated further by raising the top-blown hot spot temperature while holding the stirring energy at a certain level.

2.1.3 Establishment of high-speed and high-efficiency AOD combined blowing technology

Results of the 100-kg and 6-ton furnace tests indicate that decarburization by combined blowing can be effectively promoted by utilizing the high-temperature top-blown hot spot reaction with intense stirring at 6 kW/t or over. This finding was applied to actual AOD furnaces. First, optimum top and bottom blowing ratios were determined for the same total oxygen flow rate of 4,000 Nm³/h as used for bottom blowing. A water-cooled laval nozzle lance was adopted for hard top blowing. Fig. 5 shows the relationship between \( h/d_0 \), an index of post combustion control in top-blown converters and \( dC/dO_2 \), the amount of decarburization per oxygen flow rate at a carbon concentration of 0.5 mass % or above. The bottom-blown oxygen stirring energy \( \dot{E} \) exceeds 6 kW/t in each case, and \( d/d_0 \) is given by

\[
h/d_0 = \frac{H/d_0 - H_c/d_0}{4.12P^2 + 1.86} \quad \text{...(4)}
\]

\[
H_c/d_0 = 9.088nA(P + 1.033) \times 10^4 \quad \text{...(5)}
\]

\[
Q_{O_2} = 0.9868nA(P + 1.033) \times 10^4 \quad \text{...(6)}
\]

where \( H \) is lance gap (mm); \( H_c \) is potential core length (mm); \( h \) is free jet length (mm); \( d_0 \) is nozzle throat diameter (mm); \( P \) is nozzle front pressure (kg/cm²); \( n \) is nozzle hole number; and \( A \) is nozzle throat area (m²). As evident from Fig. 5, \( h/d_0 \) and \( dC/dO_2 \) are almost linearly related to each other, and \( dC/dO_2 \) increases with decreasing \( h/d_0 \). \( dC/dO_2 \) for combined blowing exceeds that for bottom blowing when \( h/d_0 \) is less than 60 or in the hard-blowing region.

It was confirmed that the temperature rise per unit amount of decarburization is lower in combined blowing with \( h/d_0 \) being less than 60 or in the hard-blowing region than in bottom blowing. The conventional AOD combined blowing process promotes post combustion, raises the heating rate, and retards the oxidation of chromium. The oxygen flow rate being equal, the decarburization rate is lower than achievable with only bottom blowing. The high-speed and high-efficiency AOD combined blowing process described here performs hard top blowing. The hard top blowing practice increases the amount of oxygen reacting with the steel bath by utilizing the high-temperature reaction at the top-blown hot spot, which is advantageous for decarburization, and provides a decarburization rate higher than obtainable with bottom blowing alone at the same oxygen flow rate. The new AOD combined blowing process succeeded in shortening the refining time by about 3 min and reducing the silicon reductant consumption by 1.7 kg/t.

In December 1992, the AOD waste gas cooling equipment was modified to permit total oxygen flow rates up to 9,000 Nm³/h. A high-speed combined blowing test was conducted by applying the above-mentioned combined blowing results to the AOD furnace. In the test, combined blowing was applied to the carbon concentration region of 0.05 wt% or above, the bottom-blown oxygen flow rate was kept constant at 4,000 Nm³/h, and the top-blown oxygen flow rate was varied. The lance gap was held constant at 2 m.
In Fig. 6, the test results are shown in terms of the total oxygen flow rate versus $dC/dO_2$. The values of $h/d_o$ and $L/L_0$ are also given. With the lance gap kept constant in the test, increasing the total oxygen flow rate decreased $h/d_o$, increased $L/L_0$, and produced hard blowing. Although the data vary in some degree, $dC/dO_2$ remained practically constant despite an increase in the total oxygen flow rate, resulting in increased decarburization rate and much shorter refining time. An AOD refining time of 40 min or less, including the reduction treatment, was accomplished for some grades of stainless steel.

An AOD combined blowing technology with unprecedentedly high blowing speed and efficiency was established by intensifying oxygen top blowing and enhancing the reaction of top-blown oxygen with the steel bath. It utilizes high-temperature reactions at the top-blown hot spot while maintaining the stirring intensity at a sufficiently high level.

3. Ferritic Stainless Steelmaking Technology

3.1 High-chromium hot metal dephosphorizing technology

Dephosphorization of high-chromium hot metal is strongly influenced by the carbon content of hot metal. When hot metal with a nearly saturated carbon content is used, it can be dephosphorized with a low-cost burnt lime flux. Accordingly, using a lime (CaO)-fluorspar (CaF$_2$)-iron oxide flux, basic experiment was conducted in a small furnace. It was found as a result that hot metal dephosphorization can be efficiently performed under suppressed oxidation of chromium, by increasing the oxygen weight ratio of lime to iron oxide (CaO/O) and decreasing the oxidizing power and increasing the basicity of the flux. Upon this finding, 250-ton torpedo car test was conducted at the hot metal pretreatment station of Yawata Works. The test method is as shown in Fig. 7. The test was made without making any equipment modification. A flux composed of about 60% CaO, 22% CaF$_2$ and 18% iron oxide was injected through an injection lance at the rate of about 50 kg/t, and oxygen for temperature compensation was blown through a top lance at about 4 Nm$^3$/t.

Fig. 8 shows the effect of the CaO/O ratio of injection flux (where the amount of top-blown oxygen is not included in O) on the dephosphorization volumetric rate constant and the drop of chromium content after dephosphorization. As the basic experiments did, this test show that increasing the CaO/O ratio promotes dephosphorization and suppresses the oxidation of chromium. The temperature drop was about 50K. The top-blown oxygen flow rate had little effect on dephosphorization and chromium oxidation. This is probably because the dephosphorization and decarburization reaction sites were separated in such a way that the dephosphorization reaction proceeded at the interface of the flux rising through the bath and that the decarburization reaction proceeded at the top-blown hot spot. The above results indicate that high-chromium hot metal can be efficiently dephosphorized with a limited temperature drop and chromium oxidation by optimizing the injection flux composition and utilizing top-blown oxygen.

3.2 High-efficiency and high-purity VOD steelmaking technology

Yawata Works produces ferritic stainless steel by a combination of LD-VAC and LD-OB process. Described below are the high-speed, high-efficiency VOD oxygen blowing and high-purity stainless steel manufacturing technology developed at Yawata.
Works.

3.2.1 High-efficiency stainless steelmaking technology by VOD high-speed oxygen blowing

Yawata's ferritic stainless steelmaking process consists of preliminary decarburization, chromium addition in the LD-OB furnace, finish decarburization in the VOD furnace, and continuous casting by a vertical casting machine. D.C. Hilty et al.\(^{16}\) and J. Chipman\(^{17}\) report that in stainless steel refining, the carbon content depends on the chromium content and temperature of the melt and the partial pressure of CO. As indicated by S-BOC, turndown at a high carbon content is effective in retarding chromium oxidation in the converter. The high carbon turndown means a low turndown temperature. The high carbon turndown, however, increases the VOD load and prolongs the treatment time, resulting in lower productivity in VOD. The VOD oxygen flow rate was increased to avoid a productivity drop and to optimize the distribution of the decarburization load between the converter and the VOD unit.

Fig. 9 shows the relationship between the carbon content and the decarburization oxygen efficiency in the LD-OB furnace. The decarburization oxygen efficiency decreases as the carbon content falls past the 0.7-0.8% level. Turndown around this carbon region is effective, and the wear of the converter refractory lining is reduced by lowering the turndown temperature following the Arrhenius equation\(^{18}\). Equipment modification and operating practice adopted to suit high-speed decarburization from a high-carbon region in the VOD furnace are described next. In terms of operation, measures were taken against violent spitting and overflow due to a rapid CO reaction in the bath. Namely, the shield bottom depression depth and the bottom gap were optimized to reduce the amount of metal spattering out of the system. The problem of metal overflow was solved by clarifying the overflow mechanism and controlling overflow according to the standard free energy change \(\Delta G\) involving the reduction of chromium oxide by carbon. The relationship between \(\Delta G\) and the overflow is shown in Fig. 10.

3.2.2 VOD high-purity steelmaking technology

The technology of reducing the carbon content of ferritic stainless steel to an ultralow level is described here. Stirring conditions are a predominant factor in the VOD decarburization treatment\(^{19}\) and are closely related to the implementation of high-efficiency decarburization treatment. Plant test levels are shown in Table 2. The test results are given in Fig. 11, where \(K_1\) and \(K_2\) are overall reaction rate constants for decarburization periods I and II, respectively. The carbon content is 0.14 to 0.02% in the decarburization period I and is 0.02% or less in the decarburization period II. The decarburization rate increased with increasing stirring power, except for the test levels 3 to 5 with multiple porous plugs. The decarburization reaction rate controlling step was evaluated by assuming that it can be evaluated in the same way as done by the RH reaction model of Sumida et al.\(^{20}\) The recirculation rate was calculated by the equation of Sano\(^{21}\) that was multiplied by coefficients to suit plant data.

As shown in Fig. 12, the VOD operation during the decarbu-

![Diagram](image1)

Fig. 9 Change in decarburization oxygen efficiency in converter

![Diagram](image2)

Fig. 10 Relationship between \(\Delta G\) and initial chromium content

![Diagram](image3)

Fig. 11 Effect of stirring energy on overall reaction rate constant during carburization period

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Table 2 Plant test levels

<table>
<thead>
<tr>
<th>Test level No. (Graph symbol)</th>
<th>1 (C)</th>
<th>2 (Δ)</th>
<th>3 (Θ)</th>
<th>4 (■)</th>
<th>5 (▲)</th>
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<tbody>
<tr>
<td>Central PP flow rate (Nl/min)</td>
<td>300</td>
<td>800</td>
<td>150</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Erecipic PP flow rate (Nl/min)</td>
<td>—</td>
<td>—</td>
<td>150</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Bottom-blow gas flow rate (Nl/min)</td>
<td>2.2</td>
<td>7.3</td>
<td>2.5</td>
<td>5.0</td>
<td>7.3</td>
</tr>
<tr>
<td>Top-blow gas flow rate (Nl/min)</td>
<td>247</td>
<td>303</td>
<td>278</td>
<td>278</td>
<td>303</td>
</tr>
</tbody>
</table>

PP: Porous plug
4. Manufacturing Technology of Metal Catalyst Carrier

Nippon Steel had worked on the development of stainless steel as metal support for automotive catalytic converters since 1986. As such a material, ferritic heat-resistant steel of 20% chromium-5% aluminum composition was difficult to produce by the continuous casting process. The steel is now continuously cast, rolled into foil, and fabricated into a honeycomb with a complicated thermal fatigue-resistant joint structure.

This metal catalyst carrier material is composed basically of 20% chromium, 5% aluminum, and rare-earth metals (REM).

Titanium is added to improve toughness as hot-rolled strip, and the REM content is set at 0.08% so that the highest possible oxidation resistance can be secured.

4.1 Problems with slab production

In the early stages of commercial application, the mold powder so widely varied in properties that cast slabs often had longitudinal surface cracks and cast-in slag entrapment. The slab surfaces had to be ground to the depth of more than 10 mm to get rid of such surface defects. Further, REM elements added in wire form into the molten steel in the mold occasionally enriched and segregated in the slab subsurface, and reduced the slab’s hot workability causing cracks during hot rolling.

The following were essential issues for the manufacture of metal support foil steel by the continuous casting process:

(1) Development of mold powder useful to improve the slab surface quality

(2) Development of a technique to feed REM wire into mold steel with high precision and uniformity

4.2 Development of mold powder

When high-aluminum steel is continuously cast, the aluminum of the molten steel generally reacts with the SiO₂ of the mold powder to increase the Al₂O₃ content and basicity (CaO/SiO₂ ratio) of the molten powder. The resultant increase in viscosity and melting temperature drastically lowers the lubricity an essential property of the molten powder. Since this steel contains REM as well as 5% aluminum, the viscosity and melting temperature of the mold powder are raised further. Fig. 14 shows the effects of aluminum and REM on the melting temperature of the mold powder. To prevent these changes in the mold powder property as far as possible, Li₂O, NaF and TiO₂ were added, and the Al₂O₃ and SiO₂ contents were reduced. To prevent the crystallization of Al₂O₃-MgO spinel, the MgO content was held under 5%.

4.3 Development of technique for uniformly adding REM wire into mold

When added into the ladle or tundish, REM not only are low in yield but also lead to nozzle clogging with REM oxides. They are therefore added directly into the mold in wire form. The optimum REM wire melting position was studied by fluid dynamical calculation, and the relationship between the REM wire melting position and the segregation of REM in cast slabs was evaluated. Fig. 15 shows the segregation of REM in slabs in the
5. Conclusions

The development history of stainless steelmaking technologies has been reviewed, and, in particular, the latest progress therein has been described.

1. For austenitic stainless steels, Hikari Works recorded high decarburization oxygen efficiency and short refining time by the AOD combined blowing technology that utilizes the effect of the top-blown hot spot by hard blowing, and established high-speed, high-efficiency decarburization technology.

2. For ferritic stainless steels, Yawata Works established the technology of realizing optimum load distribution between high-carbon converter turndown and high-speed VOD finish decarburization by vacuum control for prevention of VOD bumping and by intense stirring with increased ladle bottom-blown argon flow rate.

3. S-BOC was proposed as a new decarburization refining index that can explain the effectiveness of the combined blowing technology and indicate the oxidation of carbon in preference to chromium.

4. The technology whereby metal catalyst carrier can be continuously cast was established for the first time in the world through the development of an optimum mold powder and technique of adding REM wire into the mold with high precision.

References