Development of Hollow Ingot for Large Forging

By Yoshiharu IIDA,** Takemi YAMAMOTO,** Shigeyoshi YAMAURA,** Kazuo ASOH,** Jun-ichi MATSUNO*** and Takesaburo NISHIOKA****

Synopsis

A new method to make hollow ingots was developed to produce cylinder-type forgings economically. The key point of this method is the structure of the core which, consisting mainly of outer and inner steel pipes and intermediate special refractory, can readily be constructed, set in the mold and pulled out from the ingot, and which enables to control the cooling from inner surface of the ingot, without such defects as inner-side cracks.

Large hollow ingots up to 290 t can be made by this method with less segregation than that of conventional ingots and with such small porosities that close and diminish at forging ratio of about 2.

Thus, hollow ingots are utilized as materials for high grade forgings, such as pressure vessels, resulting in effective saving of production cost.

Compared with conventional ingots, hollow ingots have following characteristics of solidification;

1. Total solidification time is short.
2. Minimum solidification rate is high.
3. Final solidification is not so rapid.
4. Solidification from inner surface is slow.

Every feature in the internal quality of hollow ingot can be explained from these characteristics of solidification.

I. Introduction

Cylinder-type forgings for pressure vessels are generally manufactured in the following method; a conventional ingot is upset and punched through the axis before it is subjected to enlarging or mandrelling. This method requires a large number of heating and forging processes, but the ingot/product yield ratio is relatively low.

In order to overcome the above shortcoming, some new methods have been developed in which an ingot having a hollow axis is made first and subjected to forging process. These new methods whose variety is increasing can be divided into the following typical types:

1. A method in which a water-cooled rotation core is installed in the center of the ingot. Molten steel is fed in between the mold and core. When the solidification wall containing the core has grown to some extent, the core is continually raised and withdrawn.

2. A method in which a metal core or a sand-mold core is installed in the center of the ingot.

3. A method using a centrifugal casting technique.

4. A method in which a metal core having a round or deformed-shape horizontal cross section is placed in the center of the ingot, with the interior of the metal core designed hollow so that the hollow portion may be water-cooled before the blowing-in of cooled gas or, insertion of filling of radiant heat absorbing body, thereby adjusting solidification condition.

While these foregoing methods have been published, problems still remain, such as the complexity of making and installing the core, insufficient surface condition of the hollow ingot and internal cracks, which have been considered to make them difficult.

As a result of various researches on the core structure, the authors have succeeded in making a 140 t hollow ingot which is easy to be stripped and free from internal cracks by forming the core with sleeve and special refractory.

It is proved that segregation within these hollow ingots is much less than in conventional ingots, and that their microporosities are so small that they easily close at a forging ratio of about 2.

This paper reports on the results of investigation on the hollow ingots and internal properties of the products made with hollow ingots, and the analysis of solidification properties.

II. Manufacture of Hollow Ingot

1. Core Requirements for Casting

The core must meet the following requirements:

1. Manufacture of the core shall be easily implemented, together with installation and preparation.

2. Heat extraction from the core surface shall be controllable to the extent that internal defects, such as secondary pipe, can be prevented.

3. No cracks shall occur from stress caused by solidifying shrinkage on the ingot's inner surface, keeping the surface smooth.

4. No damage from melting or breaking during casting.

Research has been made into the possibility of manufacturing a core that will meet these requirements with economical viability. As a result, cores with a double sleeve structure were developed, as shown in Fig. 1. A special refractory is used as the filler between the double sleeves, and the inner sleeve is subjected to forced air-cooling. The outer sleeve is designed to prevent direct contact between the molten steel and the refractory. It is easily deformed

* Originally published in *Tetsu-to-Hagane*, 66 (1980), 211, in Japanese; Formerly presented to the 97th ISIJ Meeting, April 1979, at The University of Tokyo in Tokyo. English version received December 5, 1980.

** Muzushima Works, Kawasaki Steel Corporation, Kawasaki-cho, Chiba 260.

*** Research Laboratories, Kawasaki Steel Corporation, Kawasaki-cho, Chiba 260.

**** Kawasaki Steel Corporation, Kita-bonmachidorii, Chuo-ku, Kobe 651.
when heated above 1400 °C and does not resist the shrinkage of solidified shell, causing no cracks on the ingot inner surface. The refractory is selected to stand the temperatures of molten steel, and be easily removed from the sleeves after ingot stripping. The inner sleeve, which supports and makes steady the core, is kept below 800 °C by insulation with the refractory and internal cooling; thus preventing the core from buckling due to static pressure from molten steel. The sleeve is made of commercial spiral steel pipes, the refractory is available, and the core is made by simple welding and filling works. The core is set on the stool without using special equipment or tools.

It can be removed by pulling up the inner sleeve, with the refractory falling off and the outer sleeve left on the inner surface of ingot. The outer sleeve is completely removed by reheating and machining which are performed prior to and after forging, respectively. Heat extraction from the core surface is controlled by changing the refractory thickness and the cooling conditions of the inner sleeve. The core designed by the authors is completely different from any former hollow ingot manufacturing methods, in that it satisfies all requirements, being easily applicable to a manufacturing process, and yet remains economically viable.

2. Determination of the Thickness of the Core Refractory and the Cooling Conditions

Determination of the thickness of the core refractory requires investigation into two problems, i.e., ingot solidification and core strength. If the core refractory is too thick, heat extraction toward the core portion is insufficient, making the final solidifying position of the ingot malshifted toward the inner surface. If it is too thin, the temperature of the whole core becomes higher, inviting danger of core buckling, although the final solidifying position moves toward the center of the ingot thickness. Figure 2 shows the relationship, obtained by calculation, between the thickness of the core refractory in a 45 t ingot and its final solidification position which is 200 mm from the core side for a 20 mm thick refractory, and 180 mm for a 40 mm thick refractory. The above shows that even if the thickness is doubled, the final solidification point shows little change, and there is no danger of center looseness appearing on the surface. Figure 3 shows the changes in the inner sleeve temperature, together with the calculated values, when the inner sleeve is air-cooled at 1 m/sec of flow velocity using a 40 mm thick refractory.

It shows that both the measured and calculated values agree, and the temperature was saturated at about 700 °C. The calculated temperature was obtained in the process of solidification analysis which will be mentioned later in detail, and the actual one was measured by thermo-couples set on the sleeve. Figure 4 shows calculation results of relation between hot strength of double sleeves and the sleeve diameters. The condition to secure the core against buckling was estimated by stress analysis based on an elastic beam model and using mechanical properties of steel at elevated temperature. In case where core inside diameter is 300 to 600 mm, sleeve will not buckle unless the temperature of inner sleeve exceeds 1000 °C. In consequence it was determined that the inner sleeve must be air-cooled at 1 m/sec of flow velocity using a 40 mm thick refractory.

3. Ingot Teeming Requirement during Steelmaking Process

Liquid steel is teemed by bottom pouring into the hollow ingot mold shown in Fig. 1. Two to three nozzles are installed following the diameter of ingot sleeves.
on the double stool. Existing ingot mold is used. Hot top is designed to be a drop sleeve system so that weight adjustment of ingot can be possible. Hot top ratio (hot top/main body weight x 100 \%) is set at 20 \%. Core is designed to be of double sleeve structure using large diameter spiral pipe of commercial grade with various factors made to meet the foregoing conditions. Refractory that fills between two sleeves is selected with care so that it will have sufficient thermal resistance strength to liquid steel and yet be easily removed after the ingot stripping.

Figure 5 shows dimensions of hollow ingots; 20 t, 45 t and 140 t. Minimum values of core diameter are determined by the core metal strength during forging, 20 and 45 t ingots require 500 and 700 mm, respectively. Wall thickness of ingot is set at 500 mm so that cast ratio (ingot wall thickness/product wall thickness) will be 2 or over. As long as viewed from the vertical cross section, profiles determined under the above conditions feature a remarkably large height/diameter ratio of 3~6 as compared with the conventional ingot. Figure 6 shows the manufacturing process of hollow ingots. For it is to be used for high-grade forging, a special blowing process is taken at BOF for low-phosphorus, low-sulfur, and low-hydrogen contents, and then molten steel is treated with Ladle Refining Furnace (LRF) or RH-degassing, before it is proceeded to bottom pouring. Ladle temperature during pouring is designed to have a super heat of 70 to 90 °C, with the rising speed of meniscus controlled at 100 to 300 mm/min. Furthermore, reduction of non-metallic inclusion at the sedimental zone or surface layer zone is made by means of high-temperature and low-speed pouring, thereby compensating for the disadvantage caused by the increase in the height/diameter ratio of the ingot. After the completion of solidification, ingot stripping is performed following the removal of inner sleeve of the core.

### III. Quality of Hollow Ingot

The core design and cooling conditions were thus established, and large numbers of large hollow ingots up to 140 t have been produced commercially. Some of them were cut and examined on as-cast state or on test specimens from products.

1. **Appearance of Ingot**

   Ingot has a good surface because of the advantage of the high-temperature and low-speed pouring. Core surface is almost free from adhesion of refractories, and the skin of sleeve that contacts molten steel remains as it is, making it possible to be subjected to the next processes, namely, heating and forging without any conditioning.

2. **Quality of Ingot**

   Chemical compositions of hollow ingot weighing 20, 45 and 140 t, as shown in Fig. 5, are measured. The upper half of the ingot where a secondary pipe in the center and micro porosities tend to generate is examined in as-cast condition. Casting condition is shown in Table 1, and all ingots are assumed to be used for forgings for pressure vessels, of 20 t for carbon steel and 2%Cr-1%Mo steel, 45 t for 5%Cr-0.6%Mo steel, and 140 t for SFVV3 steel.

1. **Segregation**

   The C- and S-segregation conditions of 20 t carbon steel and 2%Cr-1%Mo steel are shown in Fig. 7. Figure 8 shows one of 45 and 140 t ingots. Both are investigated directly underneath the hot top and samples for analysis were taken by drills of 10 mm in diameter. C-segregation is about 130 \% directly underneath the hot top. The internal side shows a negative segregation of about 90 \% from the point directly underneath the surface to the neighborhood of the final solidification point.
2. Macrostructure
Macrostructures of 20, 45 and 140 t ingots are shown in Photo. 1. The final solidification point corresponds to 1/3 to 1/4 T (wall thickness) as previously calculated, with 12 to 14 cm from the internal surface in the case of 20 t, 15 to 18 cm in the case of 45 t, and about 30 cm in the case of 140 t ingot.

The generating condition of A-segregation shows different behaviors depending upon steel type and ingot dimensions. In other words, in the 20 t carbon steel, A-segregation occurs on both sides of the final solidification point, but in the 20 t 2%Cr-1%Mo steel, no generation of A-segregation is observed. In the 45 t ingot, it is seen only in the interior side, whereas in the 140 t ingot, the generation takes place on both sides.

3. Micro Porosity
Micro porosity within the ingot exists in the final solidification point and on the line of A-segregation. These porosities are all insignificant, about 2 mm for a relatively larger one.

3. Forging Conditions
To set up forging conditions for the hollow ingot, the bottom half of each ingot is forged at a ratio of 2 to 4M, and the conditions of closure is examined. No defects are found in Ultrasonic Test and Magnetic Particle Test, and it is confirmed that micro porosity and micro cavities are closed with forging ratio of 2M. Photographs 2 and 3 show the results of macrostructure, sulfur print, and penetration tests conducted to a 45 t hollow ingot at a forging ratio of 2M.

Table 1. Chemical composition and casting condition.

<table>
<thead>
<tr>
<th>Hollow ingot</th>
<th>Item</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 t carbon steel</td>
<td>Chemical composition (%)</td>
<td>0.20</td>
<td>0.29</td>
<td>0.96</td>
<td>0.014</td>
<td>0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 t alloy steel</td>
<td>Casting temp.</td>
<td>1590°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 t alloy steel</td>
<td>Casting time</td>
<td>7 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 t alloy steel</td>
<td>Chemical composition (%)</td>
<td>0.08</td>
<td>0.06</td>
<td>0.38</td>
<td>0.011</td>
<td>0.004</td>
<td>2.05</td>
<td>0.96</td>
</tr>
<tr>
<td>45 t alloy steel</td>
<td>Casting temp.</td>
<td>1595°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 t alloy steel</td>
<td>Casting time</td>
<td>9 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140 t alloy steel</td>
<td>Chemical composition (%)</td>
<td>0.12</td>
<td>0.07</td>
<td>0.45</td>
<td>0.011</td>
<td>0.005</td>
<td>5.02</td>
<td>0.59</td>
</tr>
<tr>
<td>140 t alloy steel</td>
<td>Casting temp.</td>
<td>1593°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140 t alloy steel</td>
<td>Casting time</td>
<td>26 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Segregation pattern of top portion. (20 t carbon steel, 20 t alloy steel)

Fig. 8. Segregation pattern of top portion. (45 t alloy steel, 140 t alloy steel)
Table 2 shows the results of mechanical test. Tensile properties are uniform in all directions of L, T and R but R-direction shows a relative reduction in impact properties. This, however, is almost on the same level as one of the ordinary forgings.

Next, the setting up of forging yield is necessary, and segregation condition of ingots is estimated using the same ingots as for the internal properties and the forging test mentioned above. Figures 9 and 10 show distributions of carbon and oxygen, respectively, in the 45 t hollow ingot. With its less segregation, and the excellent values of oxygen and cleanliness, it is
considered that about 80% of forging yield can well be possible. In this case, hot top, bottom protrusion and heating scale loss are not included. From the studies of the foregoing, forging ratio of 2 or over and forging yield of 80% can be also possible.

4. Application for Products

The results of internal property investigation and forging tests on hollow ingots prove that the manufacture of forgings with less segregation and high yield is possible. Photograph 4 shows the forging process of hollow ingot. The outer sleeve is completely cleared through forging heating, which improves workability. Products are forged using hollow ingots of 20, 45, 90, and 140 t. Table 3 shows investigation of maximum segregation ratio of carbon for ingots of 20, 45, 90 and 140 t. Maximum segregation is almost equal to the values obtained from directly underneath the hot top for internal property test. At present, processing of up-to 140 t ingot is possible with remarkably improved forging yield and workability.

IV. Solidification Property of Hollow Ingot

1. Features of Hollow Ingot

Features of characteristics of hollow ingots are as follows:

(1) Final solidification point is not in the center of the thickness but leaned to the interior side.

(2) A-segregation line tends to generate closer to the interior side rather than outer surface side.

(3) Negative segregation zone exists in the interior side.

(4) Micro porosity generation at the final solidification point is minor.

Since these are considered to attribute to the difference between solidification rate from inside and one from outside, or the difference in shape from ordinary ingot, solidification rate of hollow ingot is obtained from calculation of solidification and analyzed.

2. Method of Solidification Calculation

Assuming infinite cylinder, calculation of solidification is performed by finite difference method. When using $\phi^C (\degree C)$ for reduced temperature, and heat content $H (\text{kcal/kg})$, the basic equation (1) is as follows:

$$H_i = H_i + k_d \frac{dt}{\pi r_i} \{r_i + r_i - 1 \phi_i - \phi_i\}$$

where, $H_i$: Heat content (kcal/kg) at point $i$ after $dt$

$H_i$: Heat content (kcal/kg) at point $i$

$k_d$: Thermal conductivity temperature at standard (kcal/m • h • °C)

$\rho$: Density (kg/m$^3$)

$dt$, $dr$: Divided time (h), divided length (m)

$r_i$: Distance from the center to point $i$ (m)

$\phi_i$: Reduced temperature (°C) at point $i$.

The lattice number $i$ is either based on the center of the ingot or the innermost surface of the core. For outer point and inner point, Eqs. (2) and (3) are used, with heat flux from the surface as $q_i (\text{kcal/m²h})$.

**Outer point:**

$$H_i = H_i + k_d \cdot \frac{dt}{\rho \cdot \Delta A_i} \{r_i + r_i - 1 \phi_i - \phi_i - \phi_i - \phi_i\}$$

**Inner point:**

$$H_i = H_i + \frac{k_d \cdot \frac{dt}{\rho \cdot \Delta A_i}}{2 \cdot dr} \{r_i + r_i + 1 \phi_i + 1 - \phi_i\}$$

where, $\Delta A_i$ is a divided area between lattice point and center point per radian of center angle, and
\[ \Delta A = \frac{\pi}{2} \left( r^2 - \left( r_i - \frac{\Delta r}{2} \right)^2 \right) = \frac{\Delta r}{2} \left( r_i - \frac{\Delta r}{4} \right) \]

Inner point:
\[ \Delta A = \frac{\pi}{2} \left( \left( r_i + \frac{\Delta r}{2} \right)^2 - r_i^2 \right) = \frac{\Delta r}{2} \left( r_i + \frac{\Delta r}{4} \right). \]

In case \( \phi_i \) is radiation heat, \( q_r \) shown in Eq. (4) is used.

\[ q_r = \sigma \cdot \varepsilon \cdot 10 \left( \frac{\theta_i + 273}{100} \right)^4 - \left( \frac{\theta_a + 273}{100} \right)^4 \]  

where, \( \sigma \): Boltzmann constant (kcal/m² h °K⁴)
\( \theta_i, \theta_a \): Temperature of surface and atmosphere (°C)
\( \varepsilon \): Emissivity (-).

Heat transfer due to forced convection is considered because core interior has forced cooling of the air. Heat transfer coefficient due to forced convection is obtained by Eq. (5).

\[ h = \frac{k}{\varepsilon} \cdot Nu \]  

\[ Nu = 0.0296Re^{0.5}Pr^{1/3} \]  

where, \( Nu \): Nusselt number
\( Re \): Reynolds number \((U \times \varepsilon)\)
\( Pr \): Prandtl number = 0.71
\( k \): Heat transfer coefficient (kcal/m² h °C)
\( U \): Flow rate of the air (m/h)
\( v \): Kinematic viscosity (m²/h)
\( x \): Coordinates of the flow direction (m).

Using heat transfer coefficient \( h \) obtained by Eq. (5), heat flux \( q_a \) and total heat flux \( q_i \) due to forced convection are obtained by Eqs. (6) and (7):

\[ q_a = h(\theta_i - \theta_a) \]  

\[ q_i = q_r + q_a \]  

It is assumed that the air gap is formed between the outer surface of ingot and the ingot mold immediately after pouring and that each boundary between inner surface of ingot–outer sleeve–refractory–inner sleeve is in close contact. Conditions of calculation are shown in Table 4.

3. Results of Calculation

Calculated values of inner sleeve temperature change correspond well to the actual results as shown in Fig. 4. Also, the final solidification point (in the case of 40 mm thick refractory) as shown in Fig. 2 shows a good correspondence with the final solidification point in the macro-structure. This calculation of solidification well expresses the solidification properties of hollow ingots.

If the conventional ingot is to be used for a cylinder-type product which can be produced from a 140 t hollow ingot, it shall weigh 175 t. In terms of calculation of solidification time, a 140 t hollow ingot takes 634 min which are less than half as much as the time required for a conventional 175 t ingots 1 364 min.

Except for the period of accelerated solidification toward the end of solidification, solidification from the interior side and outer side can, respectively, be expressed in the square-root rule:

Outer side:
\[ d = 26.8 \sqrt{t} - 45 \]  

Inner side:
\[ d = 11.2 \sqrt{t} \]

where, \( d \): solidification thickness (mm)
\( t \): time (min).

Furthermore, decrease of liquid region within 30 min up to the completion of solidification is shown in Fig. 11. About 10 cm thick liquid region remains at 30 min before the completion of solidification in the case of a 140 t hollow ingot. But it reaches to a stage of complete solidification evenly. Whereas, in the case of 175 t conventional ingot, a liquid region of about 20 cm diameter makes an even reduction to 10 cm diameter, but in the next 1 min or so, it rapidly completes solidification. It is evident that the micro porosity at the final solidification point is affected by the difference in accelerated solidification in the later stage of solidification as mentioned above. In other words, in ordinary ingot, solidification is completed at a remarkably accelerated solidification rate, and during the period, micro porosity tends to be formed by bridging. In the hollow ingot, however, such micro porosity is less likely to be formed because an acceleration of any large scale does not take place. Such difference in accelerated solidification during the stage of solidification completion causes a two-

<table>
<thead>
<tr>
<th>Table 4. Conditions of calculation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial melt temperature</td>
</tr>
<tr>
<td>Other initial temperature</td>
</tr>
<tr>
<td>Liquidus temperature</td>
</tr>
<tr>
<td>Solidus temperature</td>
</tr>
<tr>
<td>Thermal conductivity (at room temperature)</td>
</tr>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>Refractory</td>
</tr>
<tr>
<td>Air</td>
</tr>
</tbody>
</table>

![Fig. 11. Decrease of liquid region at the last stage of solidification.](image-url)
dimensional solidification to the cross section of conventional ingot, whereas it causes a solidification close to one-dimension in the case of the hollow ingot.

V. Investigation

1. Forming Conditions of A-segregation Line

The forming of A-segregation line is much affected by solidification rate. Suzuki and Miyamoto proposed Eq. (10) showing A-segregation forming condition based on solidification rate \( V \) (mm/min) and cooling rate \( R \) (°C/min).

\[
RV^{1.1} < a \quad \text{......(10)}
\]

Suzuki and Miyamoto investigated a 0.7% carbon steel and obtained \( a = 8.75 \); however, as is evident from the example of the 20 t hollow ingot, the value \( a \) shall vary depending upon chemical composition.

Figure 12 shows \( RV^{1.1} \) values of hollow ingots of 20 t carbon steel and 45 t alloy steel in correspondence with A-segregation generation zone measured in macroscopic observation. In the 20 t carbon steel, A-segregation line is formed in \( RV^{1.1} < 4.0 \) zone on both inner and outer sides. In the 45 t alloy steel, it is formed in the \( RV^{1.1} < 1.1 \) zone on the inner side. \( RV^{1.1} > 1.1 \) takes place at any position on the outer side, with no occurrence of A-segregation.

The 20 t alloy steel has no A-segregation on both inner and outer sides, but since the minimum value of \( RV^{1.1} \) is 0.2, the \( a \) of this type of steel is estimated to be 0.2 or under. Therefore, the value of \( a \) which determines the forming condition of A-segregation varies according to the type of steel. However, from the fact that occurrence zone of A-segregation on the inner and outer sides is determined by the same \( a \), it is also considered that Eq. (10) is applicable for the hollow ingot, also.

Furthermore, regarding the values of Suzuki and Miyamoto also, the lower the value of carbon becomes and higher Mo becomes, the smaller becomes value \( a \). Mo, as proved by Takahashi and Kudo, is a gravity segregation inhibition element, and as by Suzuki and Miyamoto, Mo addition accelerates the formation rate of dendrite, facilitating the trapping of solute-enriched molten metal in the dendrite. Therefore, it is considered that the forming condition of A-segregation varies according to the molybdenum content also.

In order to obtain product same as the one obtained from a 45 t hollow ingot, a conventional ingot of 60 t is required. Figure 13 compares A-segregation zone between the 60 t conventional ingot and the 45 t hollow ingot. There is a possibility for A-segregation line in the region of 35 to 70 cm below surface when applying the \( RV^{1.1} \leq 1.1 \) condition to the 60 t conventional ingot. Whereas, in the case of 45 t hollow ingot, a region from 6 to 16 cm on the inner side is the A-segregation zone. The narrowness of this region is also one of the advantages of hollow ingots.

2. Forming of Negative Segregation Zone

Negative segregation zone exists on the inner side of hollow ingots. This region virtually corresponds to A-segregation line zone. Therefore, it is inferred that a slow solidification rate which causes transition of solute-enriched molten metal is a cause of negative segregation.

Actual solidification is a dendrite solidification, and the trapping of solute-enriched molten metal in the dendrite determines macro segregation. In this paper, however, Burton formula for the plane solidification is used in order to abstract only the effect of solidification rate. The Burton formula for effective distribution coefficient is as shown in Eq. (11).

\[
k = \frac{C_s}{C_L} = \frac{k_0}{k_0 + (1 - k_0) \exp (-\delta V/D)} \quad \text{......(11)}
\]

where, \( C_s \): Solute concentration in solid (wt%)

\( C_L \): Solute concentration in bulk liquid (wt%)

\( k_0 \): Equilibrium distribution coefficient (—)

\( k \): Effective distribution coefficient (—)

\( \delta \): Thickness of boundary layer for diffusion (cm)

\( V \): Solidification rate (cm/s)

\( D \): Diffusion coefficient (cm²/s)

Based on the solidification ratio \( g \), solute concentration in bulk liquid \( C_L' \) in the case that only \( dg \) is solidified is as in Eq. (12):

\[
C_L' = \frac{(1-g)C_L - dgC_s}{1-(g+dg)} = \frac{1-g-gk}{1-(g+dg)} \cdot C_L \quad \text{......(12)}
\]

The result of calculation using Eq. (12) covering from \( g = 0 \) to 1 is shown in Fig. 14. Compared with the carbon analysis results of middle ingot portion, a good correspondence is seen when \( \delta = 0.15 \) cm. Quan-
titatively, the physical significance of $\delta$ is not clear and since there is no basis which demands that $\delta$ is constant throughout the entire solidification period, it is not completely explained, but this calculation result shows that quantitatively speaking, the slow solidification rate on the inner side is the cause of negative segregation formation.

VI. Conclusion

By forming core with sleeves and special refractory, we have succeeded in the manufacture of a 200 t hollow ingot easy to strip and free from internal crack. The results of investigation on the hollow ingots reveal the following features:

1. The final solidification point is located at 1/3 to 1/4 thickness on the inner side.
2. $A$-segregation line tends to occur on the inner side rather than on the outer side, and the one on the inner side is negative segregation.
3. Micro porosity generation at the final solidification point is insignificant and minor, the maximum is only 2 mm or so in the case of 140 t ingot.
4. Segregation ratio is considerably small compared with the conventional ingot.

Furthermore, the analyses of solidification properties of hollow ingots reveal the following items:

1. Accelerated solidification at the final solidification point does not take place so conspicuously as in the case of the conventional ingots.
2. Negative segregation on the inner side is caused by the slow solidification rate which limits solute-enriched molten metal supplied by dendrite.
3. Occurrence condition of $A$-segregation is given by the $RF_{1.1}^{c} \leq \text{constant}$ which values depending on the type of steel. Since hollow ingot has a limited range of meeting the above conditions, the range of $A$-segregation occurrence is small, compared with the conventional steel ingots.

The utilization of hollow ingots which have the above features has enabled the manufacture of cylinder-type forgings at economical costs.

REFERENCES