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Synopsis :
No.3 continuous caster at Chiba Works has started its operation in April, 1981. This slab caster is one of the two which are connected with the Q-BOP process in the world. Main product of No.3 continuous caster is low-carbon aluminum-killed steel that was previously made by ingot casting. For producing low-carbon aluminum-killed steel by continuous casting connected with Q-BOP, the following techniques were established. (1) Production technique of low-carbon aluminum-killed steel which has low hydrogen content by argon gas treatment. (2) Aluminum control technique which is very accurate and gives high yield of aluminum. (3) Production technique of low and high nitrogen containing steel. (4) Production technique of low silicon steel. (Si < 0.010%) (5) Production technique of ultra low-carbon steel. (C < 25ppm)

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Production of Low-Carbon Aluminum-Killed Steel for Hot and Cold Rolled Sheets by Q-BOP–Continuous Casting Process*

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For producing low-carbon aluminum-killed steel by continuous casting connected with Q-BOP, the following techniques were established.

(1) Production technique of low-carbon aluminum-killed steel which has low hydrogen content by argon gas treatment.
(2) Aluminum control technique which is very accurate and gives high yield of aluminum.
(3) Production technique of low and high nitrogen containing steel.
(4) Production technique of low silicon steel. ($Si \leq 0.010\%$)
(5) Production technique of ultra low-carbon steel. ($C \leq 25$ ppm)

1 Introduction

The operation of the bottom-blown converter has been under way for these five years at the No. 3 Steelmaking Shop, Chiba Works, Kawasaki Steel Corporation. In this period, steel refining reactions in the bottom-blown converter were studied in comparison with those in the top-blown converter. Reports on the effects of vigorous agitation[1], the effects of flux injection[2] and the method of efficient OG gas recovery[3] were published.

In April, 1981, the No. 3 Continuous Casting Plant was put to operation in a close proximity to the bottom-blown converter[4]. Based on the judgment that the merit of the bottom-blown converter can be fully realized in the region of low carbon steel, the No. 3 Continuous Casting Plant was operated principally for the purpose of producing low-carbon steel for hot and cold rolled sheets and for coated products. In melting and casting steels for the continuous casting process, the following four items were set up as targets.

(1) To cast slabs having good surface quality even from molten steel of high H concentration
(2) To keep the tapping temperature as low as possible, in order to avoid the reduction in tuyere life
(3) To melt and cast the steels of low N ($N \leq 25$ ppm), low Si ($Si \leq 0.010\%$) and extra-low C ($C \leq 30$ ppm) at a stable rate
(4) To establish an overall cost minimum process utilizing the merit of the bottom-blown converter.

2 Basic Investigation of Hydrogen Concentration and Slab Surface Quality

2.1 Experimental method

Before starting the operation of the No. 3 Continuous Casting Plant, the effect of H concentration on the slab surface quality was investigated[5]. The low-carbon aluminum-killed molten steel produced by the top-blown converter at the No. 1 Steelmaking Shop, Chiba Works through hydrogenation with propane gas blown into the ladle or tundish, as shown in **Fig. 1**, was cast at the No. 1 Continuous Casting Plant, to examine the relationship between H concentration and slab surface quality. Besides, the low-carbon aluminum-killed molten steel produced by the

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bottom-blown converter at the No. 3 Steelmaking Shop and subjected to argon bubbling treatment in the ladle was experimentally cast into the continuous casting mold standing still in a manner similar to the ordinary ingot casting process, in order to see if there are any pinholes and blowholes.

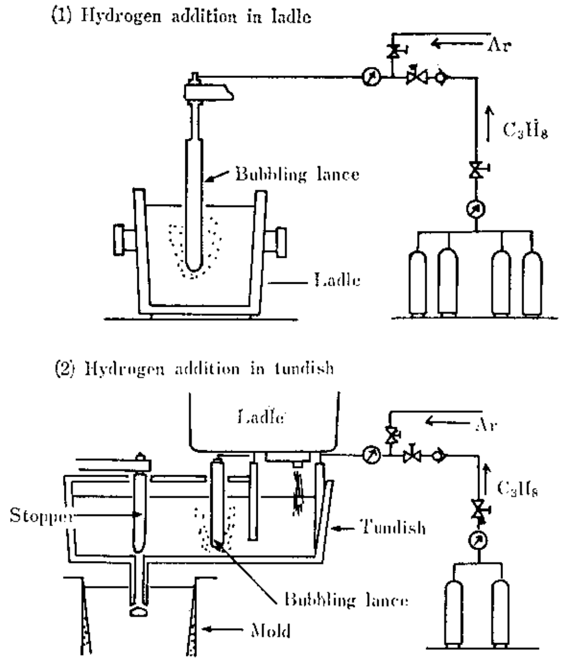

Fig. 1 Schema of experimental hydrogen addition method

2.2 Experimental Results

2.2.1 Hydrogen concentration and slab surface quality

Photo 1 shows the occurrence of blowholes in the slab's cross section. While a large number of blowholes occurred at 14 ppm H concentration (Method-d by Japan Society for the Promotion of Science: the dual tube sampling method), the sound slab was obtained at H concentration lower than 10 ppm.

Figure 2 shows the relationship between the number of pinholes on the continuous cast slab surface and the H concentration. The pinholes were detected by the liquid-penetrant method. The H concentration

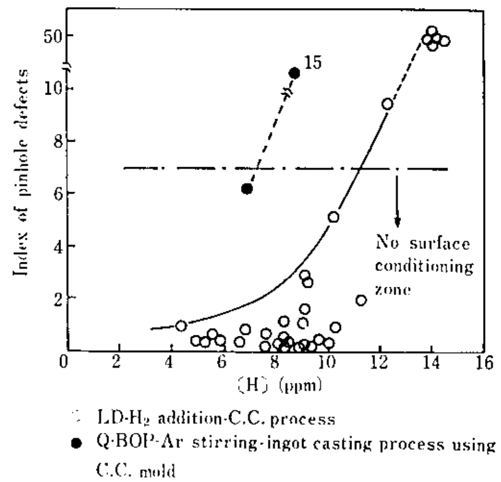

Fig. 2 Relation between H content and index of pinhole defects for low-C Al-killed steel slab

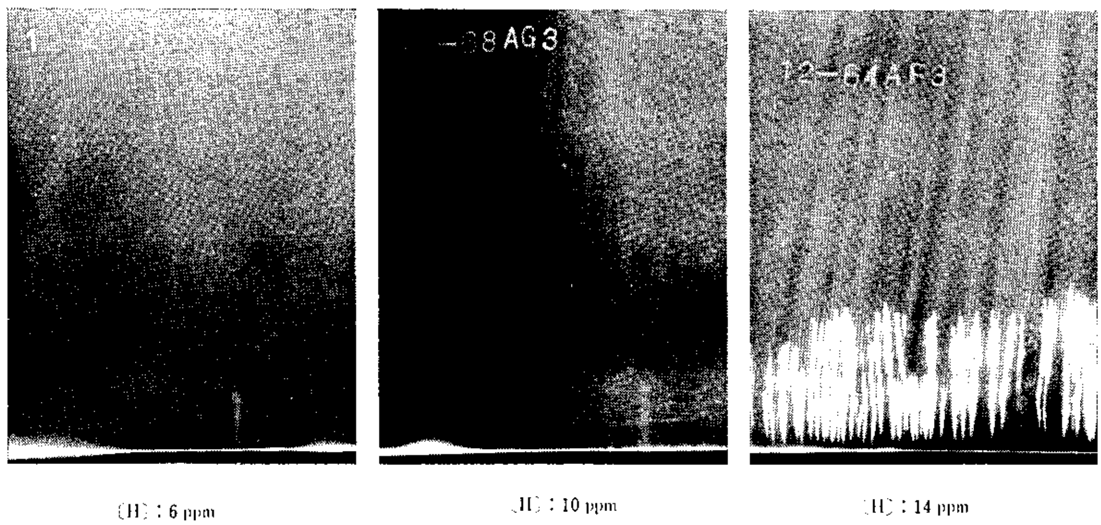

Photo 1 X-ray transmission image for detecting channel blowholes in 5 mm thick specimens cut from CC slabs

complying with the no-conditioning criteria was found to be 11 ppm in LD-H_2 addition process. However, in Q-BOP-Ar–stirring ingot casting process, the number of pinholes was greater than that in LD-H_2 addition process. This is because the molten steel flows very little in mold standing still. As the H concentration of this steel is low under the no-conditioning criteria, 11 ppm, which were obtained by the actual cotinuous casting process, it may be concluded that continuous casting of molten steel made by the bottom-blown coverter process can be realized by means of Ar bubbling in the ladle.

2.2.2 Sheet surface quality

The sheet surface quality and mechanical properties of high-H, low-C Al-killed steel with hydrogen added up to 6–10 ppm through the propane gas blowing method were examined. While the H concentration in slab was 10 ppm, it was 1 ppm or less in hot or cold rolled sheet, and the quality was the same of the steel without hydrogen added. It was confirmed that the sheet surface quality of the experimental steel was almost equal to that of the steel made through the ordinary process, presenting no problems involving defects due to blowholes.

2.2.3 Minimum hydrogen concentration for the occurrence of blowhole

The effects of H and N concentrations on the occurrence of blowholes in low-C low-Al killed steel were examined by the use of a model taking into account of the flow of molten steel in the mold.

Blowholes are supposed to occur at the solid/liquid interface of low solid phase ratio which is affected by the flow of bulk molten steel. With this point taken into consideration, the solute concentration is represented by eq. (1).

$$C_{Li} = \frac{C_{Oi}}{k_{Oi} + (1 - k_{Oi}) \exp(-R\delta_i/D_i)} \cdots (1)$$

- C_{Li}: Concentration of solute i in the liquid phase at the solidifying interface
- C_{Oi}: Concentration of solute i in the bulk molten steel
- k_{Oi}: Equilibrium distribution coefficient of solute i
- R: Solidification rate
- δ_i: Thickness of concentration boundary layer of solute i
- D_i: Diffusion coefficient of solute i

In order to evaluate the effect of molten steel flow, the thickness of flow boundary layer δ^* is converted into δ_i by using eq. (2).

$$\delta_i = (D_i/\nu)^{1/3} \cdot \delta^* \cdots (2)$$

- ν: Kinematic viscosity coefficient of molten steel

C_{Li} as defined by eqs. (1) and (2) were determined for i = H, N, C and O, and the conditions for occurrence of blowholes were analyzed by using eqs. (3)–(9).

$$P_{H_2} + P_{N_2} + P_{CO} \geq 1.0 + 10^{-6}\rho_{Fe} g y + \frac{2\sigma}{10^6 r} \cdots (3)$$

$$P_{H_2} = (C_{LH}/K_H)^2 \cdots (4)$$

$$P_{N_2} = (C_{LN}/K_N)^2 \cdots (5)$$

$$P_{CO} = K_{CO} \cdot C_{LC} \cdot C_{LO} \cdots (6)$$

$$\log K_{H_2} = -1\,673/T - 1.675 \cdots (7)$$

$$\log K_{N_2} = -188/T - 1.25 \cdots (8)$$

$$\log K_{CO} = -1\,168/T + 2.07 \cdots (9)$$

- ρ_{Fe}: Specific gravity of molten steel (g/cm^3)
- g: Acceleration of gravity (cm/s^2)
- y: Distance of molten steel surface from mold (cm)
- σ: Surface tension of molten steel (g/s^2)
- r: Radius of blowhole (cm)
- P_i: Partial pressure of i (atm)
- T: Absolute temperature of molten steel (°K)
- K_i: Equilibrium constant

Figure 3 shows the results of analysis made in the effects of H and N concentration on the critical concentration point of blowhole occurrence. The minimum H concentration in the occurrence of blowholes is about 8 ppm in the case of casting into stationary mold (flow rate of molten steel in the mold: U_0 = 3 cm/s) and about 15 ppm in the case of casting into the continuous casting mold under operation (U_0 = 40 cm/s). These values almost correspond with the

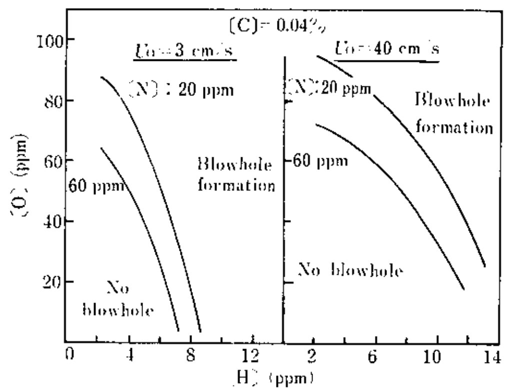

Fig. 3 Calculated effect of H, O, and N contents on blowholes formation

Table 1 Chemical composition of low-C low-Al killed steel and low-C Al-killed steel at No. 3 continuous caster connected with Q-BOP

(wt %)

	C	Si	Mn	P	S	Al	N
Low C-Low Al killed steel	0.04	0.008	0.25	0.018	0.015	0.008	0.0020
Low C-Al killed steel	0.04	0.012	0.25	0.013	0.015	0.035	0.0050

measured H concentration in low-C Al-killed steel shown in **Fig. 2**. This model can be used satisfactorily for the analysis of blowholes in steels containing H, N and O.

3 Analysis of Actual Operation

3.1 Development of in-furnace N_2 Rinse Method

Examples of representative composition of low-C, low-Al killed steel and low-C Al-killed steel are shown in **Table 1**. In the production of low C steel the concentrations of both H and O become high, because C concentration at tapping is as low as 0.03%. H affects the slab surface quality adversely, while O reduces Al yield. In order to decrease these gas components, degassing treatment with DH or RH is generally effective. However, as the rise of tapping temperature is inevitable, it is undesirable to apply the degassing treatment to all the steel types because the life of the furnace bottom is shortened.

For this reason, study was made for the application of gas blowing (N_2 rinsing in furnace for 5 sec.) after finishing blow-refining which was effective in decreasing O and H in the furnace without raising the tapping temperature.

The tapping temperature, hydrogen level and slab surface quality were compared among the following three processes:

(1) Bottom-blown converter—ladle Ar bubbling—continuous casting
(2) Bottom-blown converter (N_2 rinse in furnace for 5 sec.)—ladle Ar bubbling—continuous casting
(3) Bottom-blown converter—RH degassing— continuous casting

Tapping temperatures for the three processes are compared in **Fig. 4**. The tapping temperature of the process (2) with the 5 sec. N_2 rinse was nearly equal to that of process (1), and lower than that of process (3) with degassing.

The H concentration levels of the three processes are shown in **Fig. 5**. The H concentration of steel made by the process (2), N_2 rinse—Ar bubbling, was about 4 ppm, which was lower than that in steel made by the process (1) with Ar bubbling alone, and higher than that in steel made by the process (3) with degassing.

As for the slab surface quality, the occurrence of pinholes in steel made by bottom-blown converter (N_2

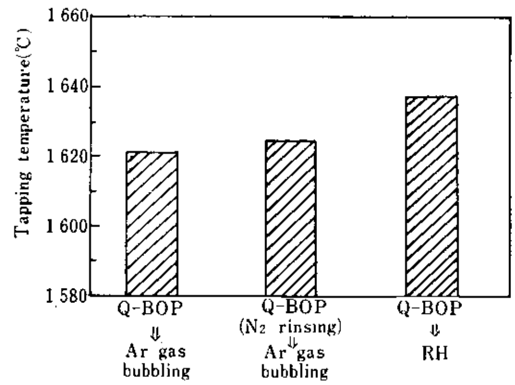

Fig. 4 Comparison of required tapping temperature

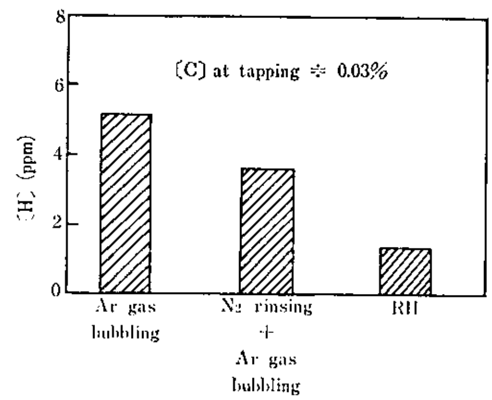

Fig. 5 Comparison of H contents in molten steel in tundish

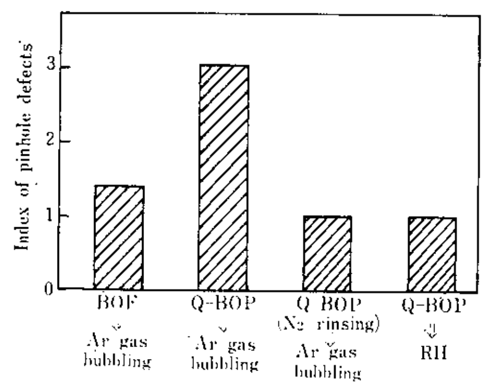

Fig. 6 Comparison of pinhole defect occurrence ratio on continuous casting slabs

rinse)—Ar bubbling was nearly equal to that in steels made by bottom-blown converter—RH and by top-blown converter—Ar bubbling, as shown in **Fig. 6**.

The effect of the 5 sec. N_2 rinse to O concentration in tapped steel is shown in **Fig. 7**. N_2 rinse reduces O concentration significantly and improves Al yield. **Figure 8** shows the distribution of Al concentration in the low-C low-Al killed steel and low-C Al-killed steel products. These values were within target value ±0.005%, with little fluctuation in Al yield.

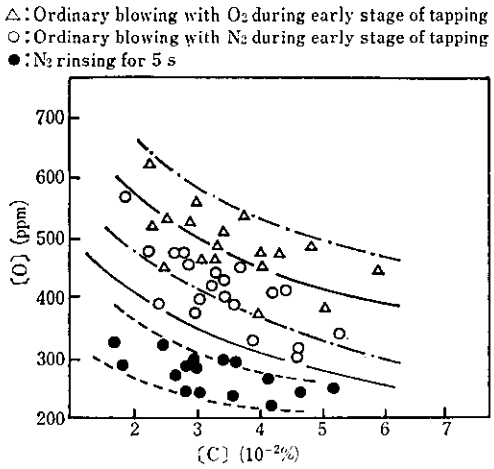

Fig. 7 Relation between C and O contents at tapping

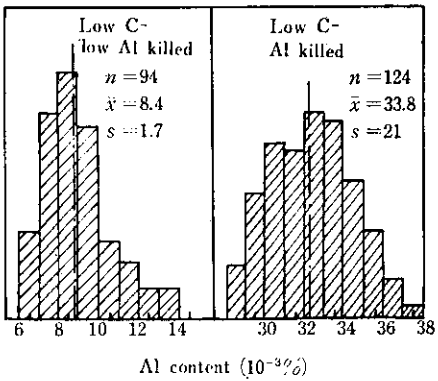

Fig. 8 Distribution of Al contents low-C low-Al killed steel and low-C Al-killed Q-BOP steel N_2-rinsed for 5 sec.

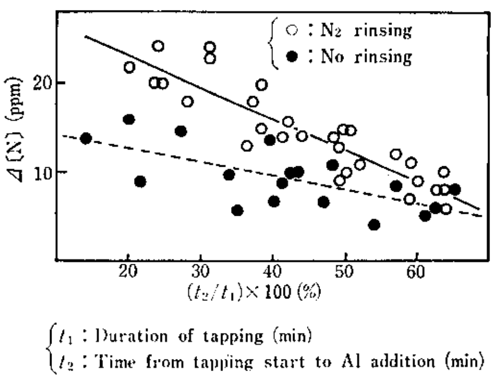

Fig. 9 N absorption during tapping in the operation of N_2 rinsing for 5 sec.

On the other hand, in case of heat with the 5 sec. N_2 rinse, as the N absorption varies extensively depending upon the timing of Al addition in the course of tapping, as shown in **Fig. 9**, it is possible to control the N absorption by changing the timing of Al addition during tapping.

3.2 Producing of Low N Steel

In order to hold N absorption at a lowest possible level, three methods of Al addition were examined.

(1) Adding all Al into ladle at the time of tapping
(2) Adding a half of Al into ladle at the time of tapping and putting the remaining half of Al wire into ladle after tapping
(3) Putting all Al as wire into ladle after tapping

The results of the experiment are shown in **Fig. 10**. For the production of low N steel, the method (3) is effective, allowing the production of low N steel including about 20 ppm N.

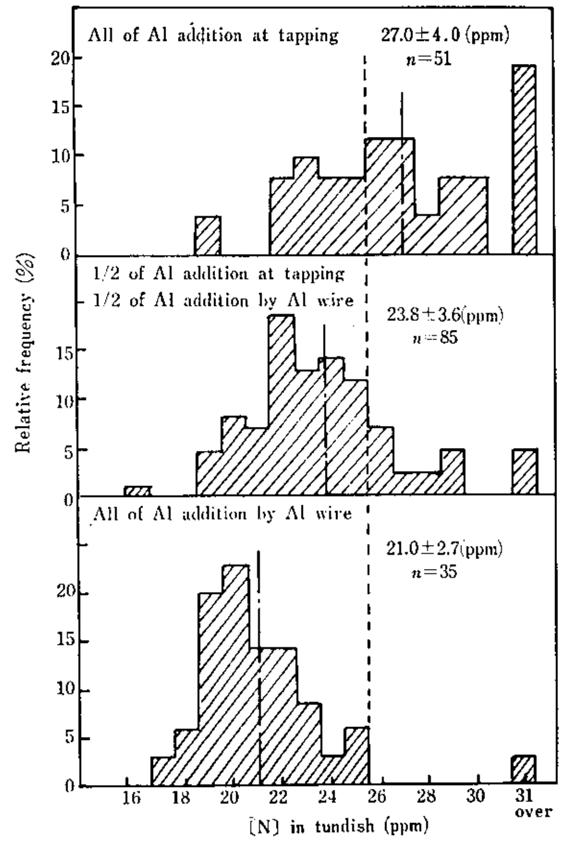

Fig. 10 Comparison of N contents between several Al addition methods after N_2 rinsing for 5 sec.

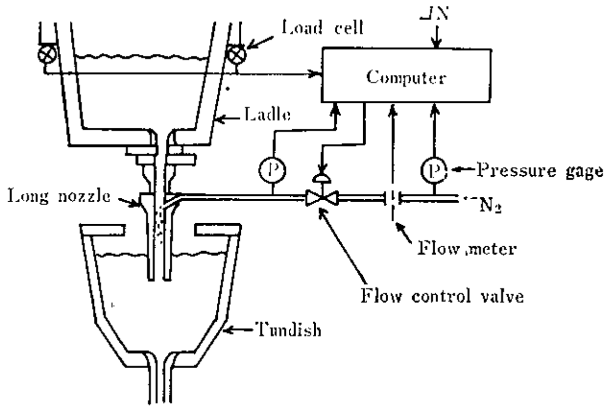

Fig. 11 Schema of N addition at long nozzle

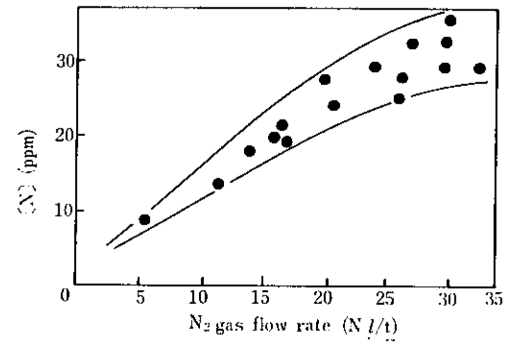

Fig. 12 Effect of N_2 gas injection into long nozzle

3.3 Producing of High N Steel

High N steel is demanded as materials for low-C Al-killed cold rolled steel sheets. Though the addition of N was usually made by feeding Mn nitride at the time of tapping, N was blown in from a long nozzle used for sealing the space between the ladle and the tundish in continuous casting, in view of cost saving. The method of adding N and its affect are shown in **Figs. 11** and **12**, respectively. After Al was added at an earlier stage of tapping, N concentration in molten steel in the ladle was analyzed and adjusted by controlling the amount of gas to be blown in from the long nozzle according to the analytical results.

3.4 Producing of Low-Al Low-Si steel

The low-Al low-Si steel is demanded as materials for galvanized steel sheets. The low-Al steel of 0.008% Al can be produced stably by the process consisting of N_2 rinse, Ar bubbling and Al wire addition.

The low-Si steel of 0.010% Si or less can also be produced by the same process described above, in which the Si restoration is suppressed, though the

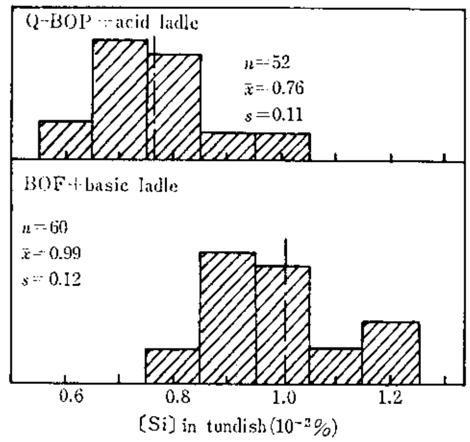

Fig. 13 Comparison of Si contents in tundish between Q-BOP steel and BOF steel

ladle is made of pyrophyllite bricks. **Figure 13** shows Si concentration in molten steel in tundish of low-Al killed steels produced by the top- and-bottom-blown converter.

The low Si steel is readily made by the bottom-blown converter because—

(1) Si concentration in steel is low at the time of tapping, and
(2) The total Fe content in slag flowing into the ladle is low and the ladle bricks are scarcely damaged.

3.5 Producing of Extra-Low Carbon Steel

While the extra deep-drawing steels have long been made by annealing in the decarburizing boxes, recent application of continuous annealing furnace make it necessary to decarburize the molten steel to the extra low level of C less than 25 ppm at the stage of steelmaking. Since there are certain advantage in favor of the bottom-blown converter such as a lower partial pressure of CO in the furnace, a higher reaction rate owing to vigorous agitation and a lower ultimate C concentration without an extensive reduction of the steel yield, the production of extra-low C steel is facilitated by the bottom-blown converter–RH degasser process[6]. **Figure 14** shows the decarburization behaviors of steel made by the top-blown converter and that made by the bottom-blown converter during the RH degassing treatment. While it takes long time to reduce C concentration in steel made in the top-blown converter to 30 ppm or less, C concentration in steel made in the bottom-blown converter can be reduced to 20 ppm by RH decarburization treatment for about 10 min. As the molten steel can be decarburized in a short time by the bottom-blown converter process in this way, multiheats-continuouscasting can be readily practiced. Moreover, owing to the short RH decarburization time, the tapping temperature

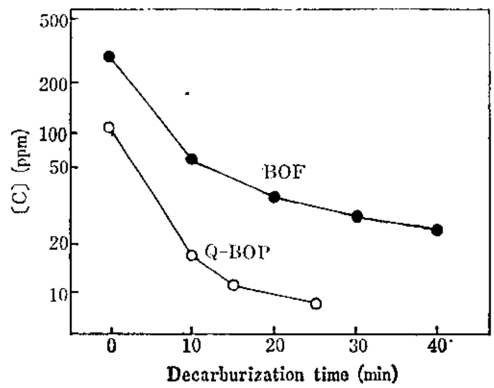

Fig. 14 Decarburization curves during RH degassing

can be decreased, which lead to advantages such as the extended life of the furnace.

4 Conclusions

The No. 3 Continuous Casting Plant clossely installed to the bottom-blown converter started its operation in April 1981 at Chiba Works. The unit is used principally for producing low-C steel for hot and cold rolled steel sheets and for coated products. For melting the steel in the bottom-blown converter for the continuous casting, the following techniques were established to cast slabs of excellent quality.

(1) The method of 5 sec. N_2 rinse in the furnace was developed to make low-C low-Al killed steel and low-C Al-killed steel of low H concentration through Ar-bubbling in the ladle. This method allows adjustment of Al at high accuracy with high Al yield.

(2) Low N steel at about 20 ppm can be made stably by feeding Al wire entirely into the ladle after tapping.

(3) The technique to adjust N was developed by blowing N_2 in from the long nozzle used for sealing the space between the ladle and the tundish. This allows the making of high N steel at low cost without using Mn nitride.

(4) Low Si steel products of 0.010% or less can be obtained through the process consisting of N_2 rinse, Ar bubbling and Al wire addition, even when using the ladle made of pyrophyllite bricks.

(5) The extra-low C steel can be made through degassing for shorter time with the tapping temperature lowered, by utilizing the merit of the bottom-blown converter such as holding the ultimate C concentration at a lower level without reducing the steel yield extensively.

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