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Increase of Stainless Steel Production Capacity in East Japan Works (Chiba)

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Abstract:

JFE Steel East Japan Works (Chiba) produces Cr-based stainless steel. Vacuum Oxygen Decarburization (VOD) which has been adopted for secondary refining performs additional decarburization while inhibiting oxidation of Cr under a high vacuum. Since production of ultra-low carbon Cr-based stainless steel which is used as a car exhaust system has been increased recently, VOD needs to process large amount of oxygen blowing with longer processing time. To improve bottleneck conditions of VOD, we tried dilution oxygen blowing, introduction of decarburization guidance, and change timing of alloy addition. As a result, more efficient production has been achieved at VOD process and productivity of stainless steel has been improved.

1. Introduction

JFE Steel's East Japan Works (Chiba District) No. 4 Steelmaking Shop (hereinafter, Chiba No. 4 Steelmaking Shop) mainly produces Cr-based (ferritic) stainless steel, and has adopted the VOD (Vacuum Oxygen Decarburization) process using top blowing oxygen for secondary refining. When producing ultra-low carbon Cr-based stainless steel, crude steel with approximately [C]=0.15 % is decarburized to 100 ppm or less by top blowing oxygen under a high vacuum. However, decarburization oxygen efficiency decreases as decarburization progresses, resulting in a refining reaction which promotes the oxidation reaction of Cr. Oxidation of Cr not only reduces the decarburization velocity, inviting delays in the treatment time, but also increases the amount of Al or Si addition for deoxidation in the decarburization process. Due to this refining reaction, when producing ultra-low carbon Cr-based stainless steel, the time required for decarburization treatment in the VOD is extended, leading to a condition which is limiting for the steelmaking process as a whole. Since shortening the decarburization treatment time is indispensable for increasing the stainless steel production capacity, in this work, we attempted to shorten the decarburization treatment time in the VOD process, and successfully achieved an increased stainless steel production capacity, as reported in the following.

2. Current Status of Stainless Steel Production Process

2.1 Flow of Stainless Steel Production Process

Figure 1 shows the flow of stainless steel production in Chiba No. 4 Steelmaking Shop[2)]. Molten pig iron from the blast furnace, which has subsequently been dephosphorized through the hot metal pretreatment process, is charged into the smelting reduction furnace (SRF), and crude steel containing chromium (Cr) is obtained by smelting reduction of Cr ore and Cr-containing dust recovered by the Oxygen Converter Gas Recovery System (OG equipment) of the converter[3)]. Next, this crude steel is charged into the decarburization furnace, and rough decarburization to around [C]=0.15 % is performed by top and bottom blowing oxygen. Following this, the steel is decarburized to approximately [C]=100 ppm while suppressing combustion of Cr by carrying out decarburization under a vacuum environment in the VOD, and final composi-

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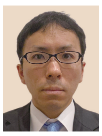
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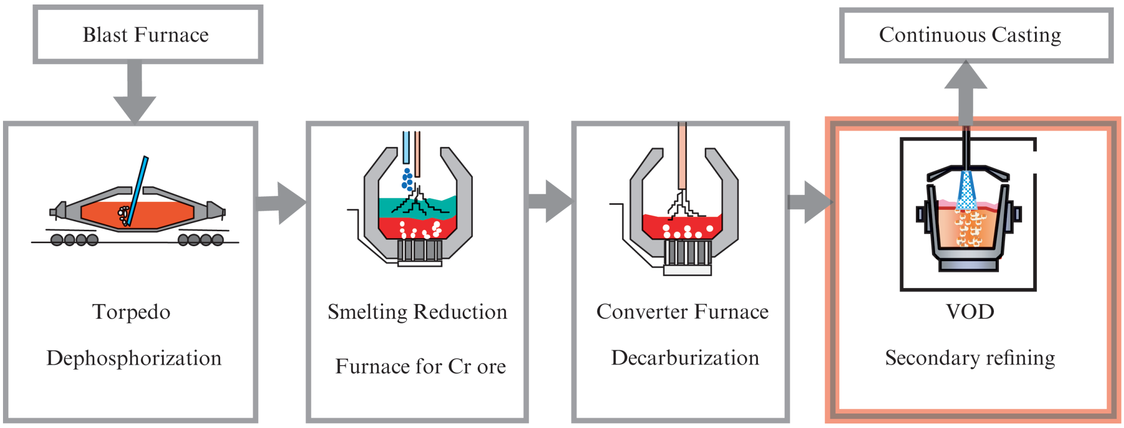

Fig. 1 Process flow of stainless steelmaking processes

tion adjustment is performed. The steel is then cast into slabs by No. 4 Continuous Caster at No. 3 Steelmaking Shop. This is the series of steps in the process flow.

An appearance of the VOD equipment used in this experiment is shown in **Fig. 2**, together with the content of treatment. VOD treatment can be broadly divided into the following processes:

(1) Vacuum decarburization by oxygen blowing: Decarburization treatment by oxygen blowing from a top blowing lance under a vacuum.

(2) Rimmed decarburization: Decarburization treatment by dissolved [O] after stopping oxygen blowing from the lance.

(3) Deoxidation: Deoxidation treatment by adding Al, Si or some other deoxidizing alloy while continuing to add the alloying elements used in the stainless steel.

(4) Treatment in the atmosphere: Final adjustment of the steel composition and temperature under atmospheric pressure.

Among these processes, this paper reports on shortening of the treatment time of vacuum decarburization.

2.2 Production Efficiency of Ultra-Low Carbon Steel

Figure 3 shows the production efficiencies of the main processes for ultra-low carbon Cr-based stainless steel, which is mainly produced at Chiba District. Here, the production efficiency of the converter is defined as the value obtained by dividing the weight of molten steel in one charge by the sum of the blowing time and the time between blowing operations. In the case of the VOD, production efficiency is the value obtained by dividing the weight of molten steel in one charge by the time required for vacuum treatment, and in continuous casting (CC), production efficiency is the value of the weight of molten steel in one charge divided by the time from the start to end of pouring into the tundish.

Comparing the production efficiencies of these processes, the VOD is inferior and therefore is the bottleneck process for the production process as a whole. This is due to the time required for vacuum decarburization of ultra-low carbon Cr-based stainless steel. Thus, it can be said that shortening the decarburization treatment time is the greatest challenge for improving productivity.

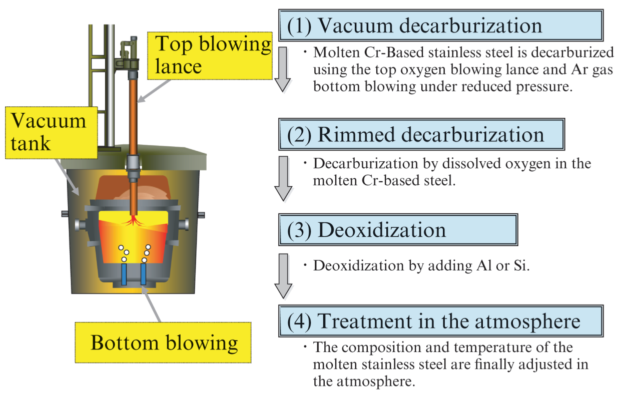

Fig. 2 Outline of VOD equipment

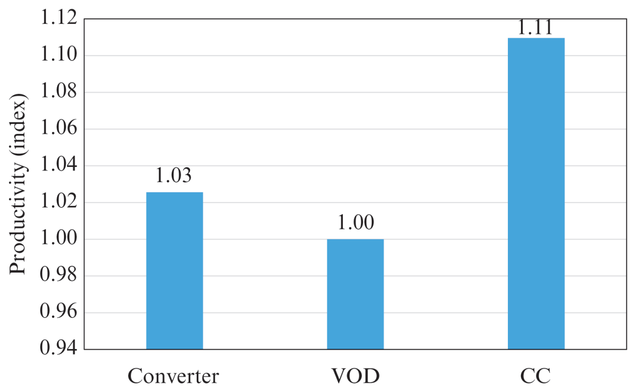

Fig. 3 Comparison of converter, VOD, and 4CC production efficiency

Table 1 Item of reduction VOD processing time

Target	Issue	Solution	Report
Low CO partial pressure	Depends on equipment performance	Ar dilution of top blowing	3.1
Low Cr concentration during decarburization	Depends on standard component	—	
Restrain excess decarburization	Judgment of decarburization end depends on operator's experimental	Installation of decarburization guidance	3.2
High temperature condition during decarburization	Temperature drop by alloy addition	Delay of timing of alloy addition	3.3
	Increase of alloy addition in Converter Furnace processing	Alloy preaddition before Converter Furnace processing	

2.3 Concept of Improvement of VOD Treatment

Decarburization of stainless steel is a competitive reaction with the oxidation of Cr. The equilibrium attainment [C] concentration is given by Eq. (1). From Eq. (1), the equilibrium [C] value decreases as a result of i) higher molten steel temperature and ii) higher vacuum (decrease of CO partial pressure). That is, the decarburization reaction velocity is considered to increase with a decreasing equilibrium attainment [C] concentration ([C]e) in Eq. (2), which expresses the decarburization reaction velocity in the first-order reaction region.

$$[C] + [O] = CO$$
$$2[Cr] + 3[O] = (Cr_2O_3)$$
$$\log K\ (= a_{Cr}{}^2 \times P_{CO}{}^3 / a_C{}^3) = -40560/T + 25.43 \quad \dots (1)$$

$$-d[C]/dt = k([C]-[C]e) \quad \dots\dots (2)$$

where, a_x is the activity of a component x, T is molten steel temperature (K), P_{CO} is the partial pressure of CO gas and [C]e is the equilibrium [C] concentration.

In ultra-low carbon Cr-based stainless steel, the upper limit value of [C] is set, and decarburization is judged to be complete based on the result of an analysis by molten steel sampling at the end of the vacuum decarburization period. Therefore, if the [C] concentration at the time of sampling is significantly lower than the allowable upper limit, vacuum decarburization was excessive, resulting in an unnecessarily prolonged treatment time. Conventionally, the operator judged the end point of decarburization by an experimental rule referring to the exhaust gas concentration, and there were large variations in the [C] value when decarburization end sampling was performed, depending on the proficiency of the operator.

Here, the fact that decarburization is a competitive reaction with oxidation of Cr appears to suggest that decarburization can be accelerated by lowering the [Cr] concentration in the molten steel. In actuality, however, it is not possible to reduce [Cr] because the [Cr] range is determined by the product standard.

Summarizing the above, the targets of this work and measures to achieve them are considered to be as shown in **Table 1**. Among these, this report discusses Ar dilution of oxygen in top blowing under a vacuum (dilution oxygen blowing), introduction of decarburization guidance, and change (delay) if the timing of alloy addition during decarburization treatment.

3. Experiments

3.1 Dilution Oxygen Top Blowing Under Vacuum

3.1.1 Outline of dilution oxygen blowing[4)]

First, dilution oxygen blowing will be explained in detail. Vacuum oxygen decarburization (VOD) treatment is broadly classified into two periods, depending on the [C] region during treatment. The first is called Oxygen blowing 1, and is the period in which the decarburization velocity depends on the O_2 blowing rate because the O_2 supply is the rate-limiting step for the decarburization velocity in the high [C] region. The second, Oxygen blowing 2, is the period when the decarburization velocity is limited by the transfer of [C] in the low [C] region, in other words, the decarburization velocity is decided by the difference of concentration between the [C] value of the molten steel and the equilibrium [C] value.

In this experiment, it was thought that the effect of dilution O_2 blowing cannot be obtained during Oxygen blowing 1 because the O_2 supply is the rate-limiting step in that period. Therefore, we attempted to increase the decarburization velocity by reducing the CO partial pressure, that is, by reducing the equilibrium [C], by performing mixed blowing of O_2+Ar during the period when only O_2 had been blown in the conventional method in the Oxygen blowing 2 period.

The conditions used in the experiment are shown in **Table 2**. If only Ar was increased to 10 Nm^3/min during Oxygen blowing 2, it was thought that splashing from the molten steel increased, and there was concern that the increase in the amount of skull adhering to the

Table 2 Pattern of dilution oxygen blowing

		Oxygen blowing 1	Oxygen blowing 2
Convention	O_2 blowing velocity (Nm^3/min)	25	18
	Lance height (mm)	1 500	1 450
Experiment	O_2 blowing velocity (Nm^3/min)	25	15
	Ar blowing velocity (Nm^3/min)	0	10
	Lance height (mm)	1 500	1 650

inner lid of the VOD would invite production trouble. (The "inner lid" is a refractory-lined lid installed at the top of the ladle.) To avoid this problem, the O_2 blowing velocity was decreased from 18 to 15 Nm^3/min and the lance height was increased from 1 450 mm to 1 650 mm. These conditions are based on a calculation that the dynamic pressure of the bath surface would be the same as in the standard process. This measure, in which Ar is mixed with O_2 and the O_2 blowing velocity is reduced, is called dilution oxygen blowing.

Dilution oxygen blowing was performed under the above-mentioned conditions with ultra-low carbon Cr-based stainless steel with a [C] upper limit of 150 ppm.

3.1.2 Results of experiment

Figure 4 shows the change in the decarburization velocity in this experiment. A tendency in which the decarburization velocity increases by 14 % can be seen under the dilution oxygen blowing condition. Because the life of the inner lid of the VOD equipment did not decrease with continued dilution oxygen blowing, it is thought that the amount of molten steel splash did not increase. The decarburization treatment time was shortened by 3.5 % by this experiment.

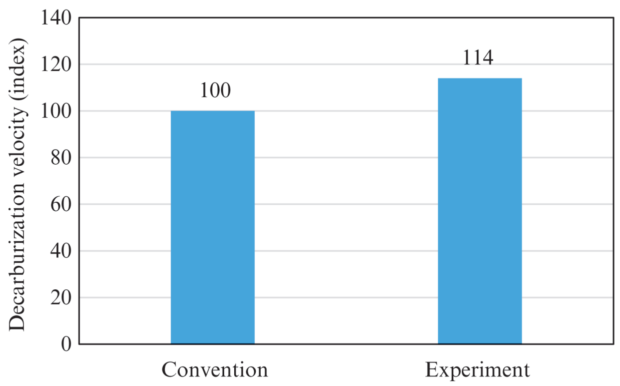

Fig. 4 Effect of decarburization velocity index by dilution oxygen blowing

3.2 Preparation of Guidance to Prevent Excessive Decarburization

3.2.1 Outline of decarburization guidance[5)]

Next, the final [C] of the VOD process was optimized to prevent excessive decarburization. In the case of ultra-low carbon Cr-based stainless steel, many standards specify an upper limit of 150 ppm for [C]. Sampling is carried out at the end of vacuum decarburization (process (1) in section 2.1), and blowing is completed and the process transitions to rimmed decarburization midway through the waiting period of approximately 10 minutes for the analysis results. If the [C] value in the analysis results is lower than the limit value, the process proceeds to deoxidation. On the other hand, if the [C] value is higher, vacuum oxygen blowing is performed again, after which the process continues to deoxidation. Since the CO_2 concentration in the exhaust gas linearly decreases at the end of decarburization, the timing of sampling at the end of oxygen blowing in the conventional method had been decided from the CO_2 concentration in the exhaust gas (**Fig. 5**). However, even when compared at the same CO_2 concentration, there are large variations in the [C] analysis results due to the effects of the molten steel temperature, the degree of vacuum and other factors. Therefore, in cases where the [C] analysis results trend higher than the estimated value, it is necessary to perform decarburization treatment again, which results in a prolonged treatment time. For this reason, excessive decarburization had been carried out so that repeated decarburization would not be necessary if the variations in [C] trended at a high level.

In this experiment, we thought it would be possible to shorten the treatment time by improving the hitting accuracy of the final [C] value of VOD so as to prevent

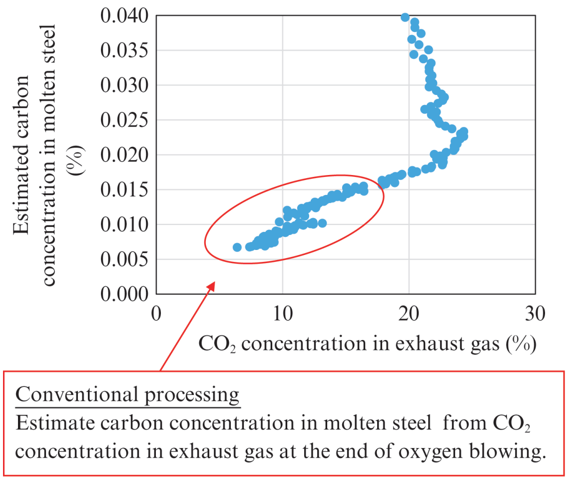

Fig. 5 Relationship between estimated carbon concentration in molten steel and CO_2 concentration in exhaust gas

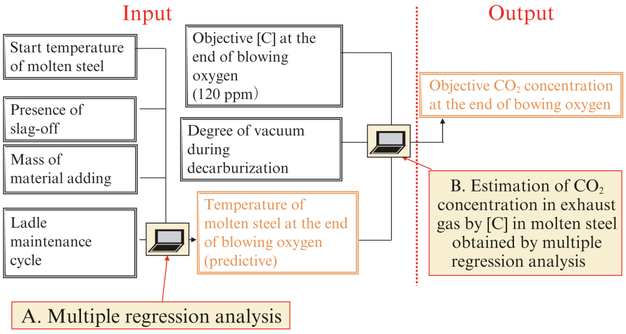

Fig. 6 Outline of decarburization guidance

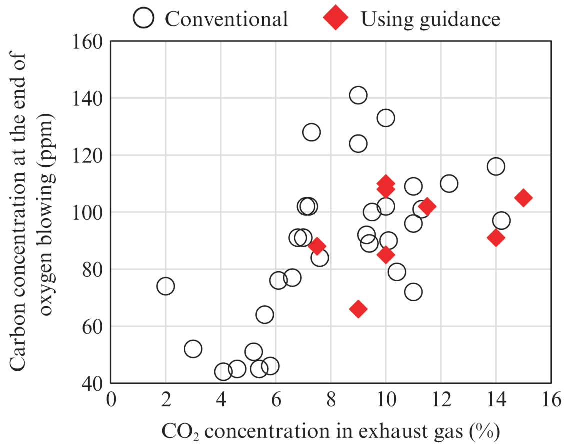

Fig. 7 Relationship between CO_2 concentration exhaust gas and carbon concentration at the end of blowing oxygen

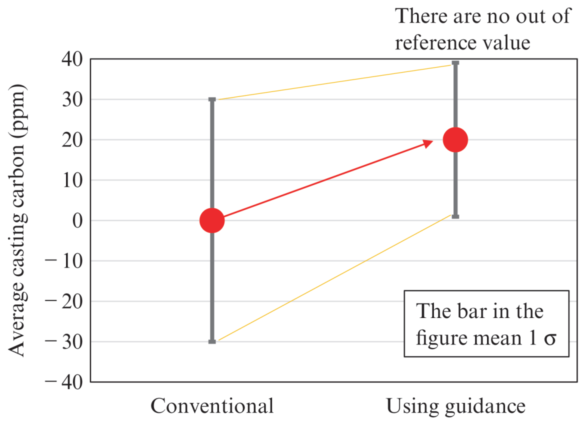

Fig. 8 Transition of casting [C] value after application of decarburization guidance

excessive decarburization, and prepared decarburization guidance for estimating the [C] value at the end of decarburization by selecting factors having a correlation with the decarburization reaction and performing a multiple regression analysis. The concept of decarburization guidance is shown in **Fig. 6**. The optimum timing for performing sampling is provided by the guidance based on the assumption that the factor which the operator finally judges is the CO_2 concentration in the exhaust gas. It was decided that the guidance indicates the optimum timing for sampling. The factors that influence the exhaust gas CO_2 concentration are i) Target value of [C] in sampling at the end of oxygen blowing (here, the aimed value was [C]=120 ppm), ii) Degree of vacuum during decarburization and iii) Molten steel temperature at the time of sampling. Among these factors, because the molten steel temperature is known for the first time at the time of sampling, this value must also be predicted by multiple regression. The factors that influence the molten steel temperature include iv) Molten steel temperature before treatment, v) Deslagging before VOD treatment to remove slag carried over from the converter, vi) Amount of alloys added during oxygen blowing and vii) Period when the ladle remained empty.

Based on the above, the method of operating the guidance is as follows.

(1) The above-mentioned factors i) to vii) during VOD treatment are input into a personal computer, which calculates the CO_2 concentration at the timing when sampling should be performed.
(2) Sampling is carried out at the end of vacuum decarburization at the timing calculated in (a). Oxygen blowing and rimmed treatment are completed during the 10 minute period while the analysis results are determined.
(3) The analysis results are determined, and upon confirmation that the result is [C]=120 ppm or less, the process proceeds directly to deoxidation.

The experiment was performed with ultra-low carbon Cr-based stainless steel by the method outlined above.

3.2.2 Results of introduction of guidance

Figure 7 shows the actual results of the exhaust gas CO_2 concentration (%) at the time of sampling at the end of decarburization and the final [C] value of VOD before and after the introduction of decarburization guidance. Application of decarburization guidance enabled sampling in a condition in which the exhaust gas CO_2 concentration is high, and as a result, the final [C] value of VOD is also high. Furthermore, before application of decarburization guidance, the variations in the [C] value were large, at 70 to 140 ppm, in the region where the CO_2 concentration was 7 to 15 %, but this decreased to 60 to 110 ppm after application of guidance. This shows that variations in the sampling [C] value were reduced by applying the guidance, and as a result, the [C] value could be controlled to a higher level. **Figure 8** shows the average casting [C] values before and after introduction of the guidance. There were no out-of-standard [C] values after introduction of the guidance. Decarburization treatment time could be shortened by 6.9 % by introduction of this guidance.

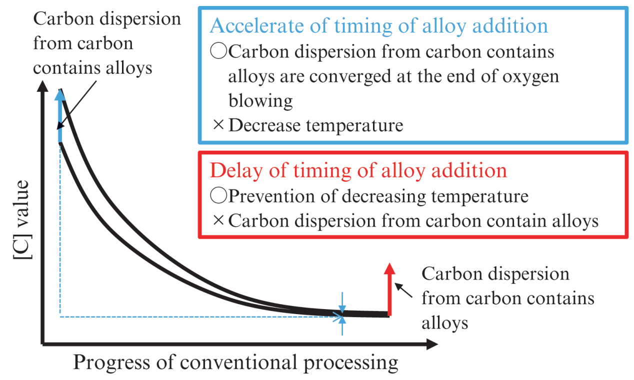

Fig. 9 Effect of delay timing of alloy addition

Table 3 Effect of delay timing of alloy addition

Item	Decarburization time	Procedure
1. Decarburization efficiency	−0.15	Calculate decarburization efficiency from temperature transition
2. Decarburization time of carbon from added alloy	+0.08	Calculate decarburization efficiency of beginning and late decarburization temperature
Total	−0.07	

Conventional decarburization time means 1.0

3.3 Change of Timing of Alloy Addition During Treatment

3.3.1 Outline of Delayed Alloy Addition Timing Experiment[5)]

Next, the timing of alloy addition during vacuum decarburization was changed. Conventionally, alloy had been added at the start of oxygen blowing in order to minimize the effect of the C component contained in the alloy added during blowing. However, the effect of the temperature drop in the initial oxygen blowing period had caused deterioration of decarburization oxygen efficiency. As a measure for this, it was thought that [C] would not exceed the upper limit value if the alloy was added at the end of blowing because the introduction of the above-mentioned decarburization guidance made it possible to judge the end of decarburization with higher accuracy and hold variations in the final [C] of VOD to a low level. **Figure 9** shows a conceptual diagram of the effect of delay timing of alloy addition. In the conventional alloy addition at the start of oxygen blowing, the [C] pickup effect of the trace amount of C contained in the alloy converged at the end of oxygen blowing, and variations in the [C] value could be suppressed. However, on the other hand, this timing had invited a decrease in decarburization oxygen efficiency due to the decrease in the temperature of the molten steel.

As a measure for this, in alloy addition in the final period of oxygen blowing, although pickup of [C] due to the C content of the alloy was high, it was thought that deterioration of decarburization oxygen efficiency could be prevented because the temperature of the molten steel could be maintained at a high level until the end of decarburization.

3.3.2 Results of experiment

In the study described above, we considered both i) the effect of the increase in decarburization oxygen efficiency by the increase in the molten steel temperature and ii) the effect of the increase in decarburization time due to the C content of the alloy, and calculated the degree of those respective effects on decarburization time. The results are shown in **Table 3**. Because a 7 % reduction in decarburization time could be maintained, we judged that it is possible to shorten the treatment time in VOD by delaying the timing of alloy addition. As a result of this change in the timing of alloy addition, decarburization oxygen efficiency during VOD vacuum oxygen blowing increased by 20 %, and decarburization time could be shortened by 7.3 %.

4. Summary of Results

Three experiments were conducted from the viewpoints of improvement of decarburization efficiency in vacuum decarburization in the VOD process and prevention of excessive decarburization, and the following improvements in production efficiency were achieved.

Production efficiency in VOD treatment was improved by i) 3.6 % by dilution oxygen blowing, ii) 8.0 % by introduction of decarburization guidance and iii) 9.9 % by delaying the timing of alloy addition. As a result, the production efficiency of the VOD process was improved by a total of 22 %, and the bottleneck condition in which the VOD was the limiting process in stainless steel production was eliminated (**Fig. 10**).

5. Conclusion

Various approaches for shortening the VOD treatment time of ultra-low carbon Cr-based stainless steel were examined, and the following knowledge was obtained.

(1) Dilution oxygen blowing in the vacuum decarburization process made it possible to accelerate decarburization by creating a low CO partial pressure condition. As a result, operational trouble caused by skull buildup and splashed slag could be prevented, while also maintaining decarburization

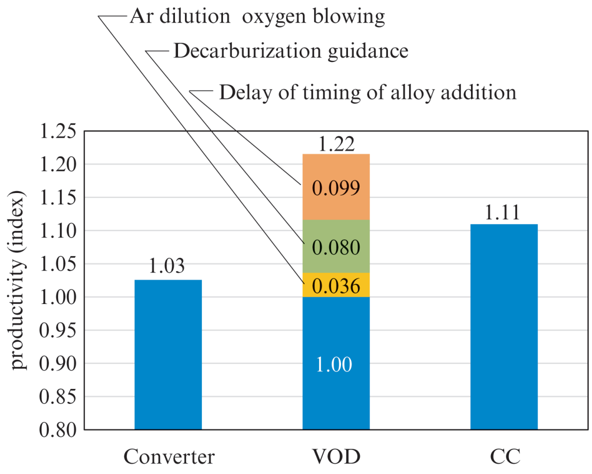

Fig. 10 Result of improvement of VOD processing

oxygen efficiency at a high level. Production efficiency was improved by 3.6 % by this measure.

(2) The timing of sampling at the end of decarburization could be optimized by providing decarburization guidance. As a result, it was possible to prevent excessive decarburization without the occurrence of out-of-standard [C] values, thereby achieving an 8.0 % improvement in production efficiency.

(3) Delaying the timing of alloy addition to improve decarburization oxygen efficiency by maintaining a high molten steel temperature during oxygen blowing was also examined, resulting in a 9.9 % improvement in productivity.

Although the low productivity of the VOD process had been the limiting factor for the productivity of the ultra-low carbon Cr-based stainless steel production process, the production efficiency of the VOD process was improved by a total of 22 % as a result of these experiments, and the bottleneck condition of the VOD was successfully eliminated.

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