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Recent Progress of Stainless Steelmaking Process at Kawasaki Steel

Masanori Nishikoori, Hiroshi Nishikawa, Ken-ichi Sorimachi

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Masanori Nishikoori
Steelmaking Technology Sec., Steelmaking Dept., Chiba Works

Hiroshi Nishikawa
Manager, Steelmaking Sec. I, Steelmaking Dept., Chiba Works

Ken-ichi Sorimachi
Dr. Eng., Chief of Steelmaking Lab., Ironmaking & Steelmaking Res. Dept., Iron & Steel Res. Labs.

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1 Introduction

In 1981, Kawasaki Steel Corporation consolidated its stainless steelmaking operations at Chiba Works and carried out an equipment modernization at No. 1 Steelmaking Shop, centering on the revamping of the shop's two 85-t LD furnaces as top-and-bottom blowing K-BOP converters.[1)] This made it possible to refine stainless steel by the MF/K-BOP process (MF: electric arc melting furnace) based on an integrated iron and steelmaking system. Thereafter, various development work and product improvements were carried out under a fundamental policy for technical development in the field of stainless steel production of (1) increased productivity, (2) flexible choice of inexpensive raw materials, and (3) energy saving by reducing electric power consumption. As a result, Kawasaki steel developed an economical heat compensation technique for the K-BOP using dephosphorized hot metal, a high-speed blowing technique, and others, thereby establishing the basis for a rational, high-productivity stainless steel refining technology.[2,3)] Based on the accumulation of these techniques and with the aim of further improving productivity and saving energy, Kawasaki Steel developed a smelting reduction process for chromium ore[4)] and optimized operating conditions, and introduced the KTB top oxygen blowing method using the top lance in the vacuum degasser,[5)] establishing a combined decarburization process for stainless steel by the K-BOP–KTB method, which makes maximum use of the advantages of being located in an integrated steelworks.

These technical developments were combined to create a rational, stable production system which permits selection of the optimum process for all steel grades and is capable of meeting today's increasingly strict quality requirements for stainless steel.

This report presents an outline of the most recent stainless steelmaking processes at Kawasaki Steel.

2 Stainless Steelmaking Process at Chiba Works

The process flow for stainless steelmaking at Chiba Works No. 1 Steelmaking Shop is shown in **Fig. 1**. The specifications of the main equipment are given in **Table 1**.

Smelting reduction is a main process, and is used to refine stainless steel using Cr pellets obtained by prereducing Cr ore to the 65–70% level with a rotary kiln as the Cr source. One of two K-BOPs serves as the smelting reduction furnace, while the other is used for decarburization. In the smelting reduction furnace, after first charging hot metal dephosphorized in the hot metal pretreatment process, continuous reduction smelting is performed by continuously charging coke, which

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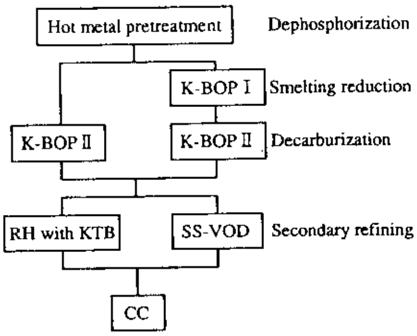

Fig. 1 Process for stainless steelmaking at Chiba Works

Table 1 Specifications on the main equipment of stainless steelmaking facilities at Chiba Works

Items	Specifications
Hot metal treatment	Torpedo injection (ATH type)
Flux	CaO based flux
Injection rate (max.)	500 kg/min
Oxygen flow rate (max.)	50 Nm^3/min
Converter (K-BOP I)	Smelting reduction furnace
Capacity	85t (combined blowing)
Oxygen flow rate (max.)	300 Nm^3/min (top lance) 100 Nm^3/min (bottom tuyere)
Bottom gas	O_2, N_2, Ar
Waste gas treatment	OG type
Converter (K-BOP II)	Decarburization furnace
Capacity	85t (combined blowing)
Oxygen flow rate (max.)	230 Nm^3/min (top lance) 100 Nm^3/min (bottom tuyere)
Bottom gas	O_2, N_2, Ar
Waste gas treatment	OG type
Secondary refining	● RH degasser with KTB ● Strongly stirred VOD ● Ladle flux injection
Continuous casting	Curved mold slab caster
Maker	Sumitomo-Concast
Number of strand	1 strand
Machine length	19.5 m
Slab size	195 — 260 mm thickness 680 — 1700 mm wide

serves as a reducing agent and heat source, simultaneously with Cr pellets. After slagging off, the Cr-containing crude steel tapped from the smelting reduction furance is charged into the decarburization funace for decarburization refining. The secondary refining facilities comprise an RH degasser equipped for oxygen top blowing through the top lance (KTB process) and an SS-VOD (strongly stirred VOD). Thus, stainless steel is produced by a composite decarburization process which includes the K-BOP and these oxygen-supplied vacuum decarburization facilities.

Table 2 Process application for stainless steel grades

Process	Stainless steel grades
K-BOP I − K-BOP II − KTB (K-BOP II − KTB)	Normal stainless steel SUS304(L), SUS316(L), SUS321, SUS410, SUS420, SUS430, SUS434, SUS436L SUH409, etc.
K-BOP I − K-BOP II − SS-VOD (K-BOP II − SS-VOD)	Ultra low carbon, nitrogen stainless steel SUS447J_1, SUS444, 20%Cr-5%Al steel, etc.

The availability of the equipment described above provides a number of process route choices, making it possible to use the most appropriate process for the grade of steel being produced and raw material conditions. For example, a process composed of the smelting reduction of Cr ore and composite decarburization by the K-BOP−KTB is selected for general stainless steels such as SUS304 and SUS430, while the K-BOP−SS-VOD is selected for high-purity high-Cr ultra-low carbon, low nitrogen stainless steels such as SUS447J_1 and SUS444. The main processes and subject steel grades are shown in **Table 2**.

3 Operation of Smelting Reduction Furnace

3.1 Material Mix for Smelting Reduction Process

The smelting reduction process has the advantages of high productivity, because an electric furnace is not used, and a wide degree of freedom in the selection of raw materials; other outstanding features include the possibility of using inexpensive Cr sources and incorporating large amounts of stainless steel scrap and low-grade scrap in the material mix.[4] **Table 3** shows an example of the respective material mixes with the MF−K-BOP and the smelting reduction process. Because the

Table 3 Material mix of stainless steelmaking process (kg/t)

	MF−K-BOP			SC+SR		
	MF	K-BOP	Total	K-BOP I	K-BOP II	Total
Normal scrap	351	—	351	—	—	—
Stainless scrap	333	—	333	240	125	365
Cr-pellet	—	—	—	260	—	260
Alloy	260	98	358	—	245	245
Hot metal	—	930	—	400 (51.5%)[a]	720 (66.0%)[a]	400 (34.5%)[a]

[a] Hot ratio

smelting reduction process melts scrap in the smelting reduction furnace using coke as the heat source, and can also melt scrap in the decarburizing furnace, taking advantage of the excess heat associated with a reduction in alloy charging, it is possible to employ substantially the same ratio of stainless steel scrap as in the MF−K-BOP route.

3.2 Optimization of Smelting Reduction Furnace Operation

The blowing pattern in the smelting reduction furnace and changes in chemical composition are shown in **Figs. 2** and **3**, respectively. The Cr pellet and the small-lump coke which serves as the heat source are charged at a fixed rate relative to the oxygen supply rate, and control of this ratio makes it possible to control temperature with good accuracy.

Smelting reduction refining is broadly divided into three periods: the scrap melting period, during which the temperature of the steel bath is increased to a prescribed temperature while the stainless steel scrap melting proceeds; the smelting reduction period, when the Cr pellets are reduced while maintaining a set bath temperature; and the finishing reduction periods, when the slag is reconstituted with the aim of recovering any chromium oxide remaining in the slag and preventing powdering during cooling of the formed slag. Molten steel with a 16% [Cr] is obtained as a final result.

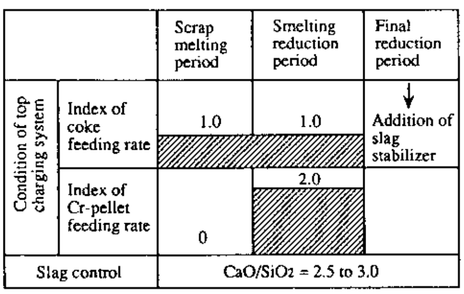

Fig. 2 Blowing pattern of smelting reduction

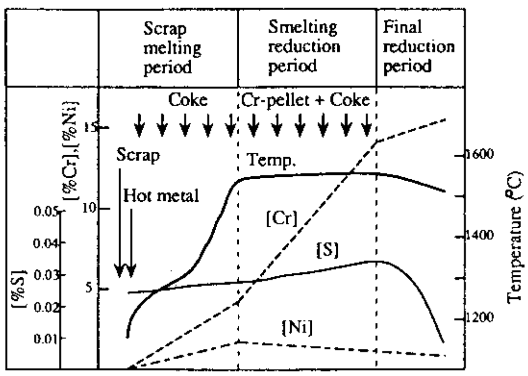

Fig. 3 Change in chemical composition and temperature of molten bath

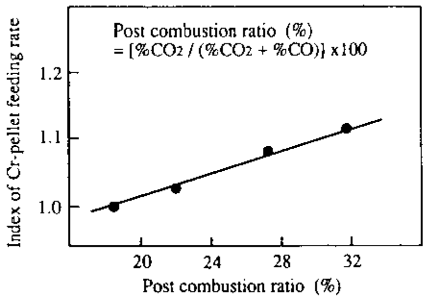

Fig. 4 Relationship between post combustion ratio and Cr-pellet feeding rate

Because the rate of Cr pellet charging is determined by the heat balance in the furnace, it is important to increase the amount of heat generated in the furnace by promoting post-combustion.[6] For this reason, an investigation was made of the relationship between the rate of Cr pellet feeding, which creates the heat balance, and the post-combustion ratio by varying the conditions of oxygen supply from the top lance. The results are shown in **Fig. 4**. It is possible to increase the Cr pellet feeding rate by 9.2% for each 10% increase in the post-combustion ratio. Operation in which the lance is held in a high position (high lance-height operation) is advantageous for enhancing the post-combustion ratio. On the other hand, the increase in the amount of heat generated in the furnace is considered to have a adverse effect on refractories. Active efforts are therefore now being made to improve the refractories themselves, and operations are carried out with the lance raised only within the range where it will not affect the refractories.

4 Adoption of Combined Decarburization Process with K-BOP−KTB

4.1 Outline of Combined Decarburization Process with K-BOP−KTB

In the smelting reduction process, high-Cr crude steel tapped from the smelting reduction furnace is charged into the decarburization furnace after slag-off, and decarburization is performed. In order to decrease the oxidation loss of Cr which occurs during decarburization refining in the furnace and to reduce the consumption of FeSi alloy for reduction, efforts were made to optimize the bottom blowing gas flow rate and the number of tuyeres,[7] to increase the direct tapping ratio (i.e. tapping without sampling),[8] and to establish a N_2-oxygen decarburization method which does not use costly Ar gas.

However, in an effort to further rationalize the refining process, composite decarburization was introduced using the K-BOP−KTB method, which combines Ar/N_2-oxygen decarburization in the decarburization furnace (K-BOP) and top oxygen blowing with the top lance in the RH degassing vessel (KTB). **Figure 5** shows a sche-

Oxygen flow rate	5-25 Nm^3/min
Lance height	2.1 - 3.6 m
Lance	Water cooled
Lance tip profile	Single laval nozzle

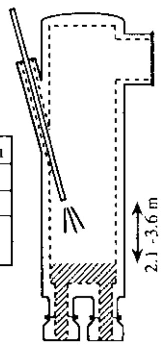

Fig. 5 Schematic illustration of KTB

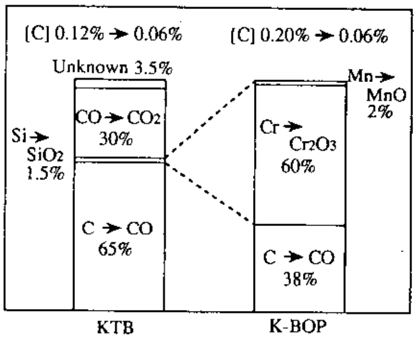

Fig. 8 Comparison of oxygen balance between KTB and K-BOP (SUS430 grade)

matic illustration and the main specifications of the KTB equipment installed on Chiba Works No. 1 RH. Because oxygen-supplied decarburization had depended completely on the K-BOP in the formerly-used process, the oxygen efficiency for decarburization dropped sharply in the low carbon-content region, as shown in **Fig. 6**, but with the introduction of the composite

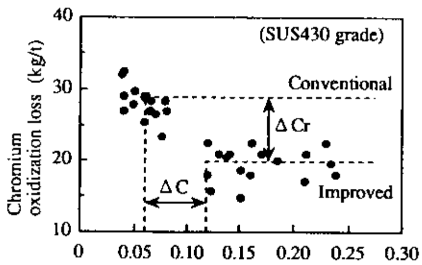

Fig. 9 Effect of tapping carbon content on chromium oxidization loss in K-BOP (SUS430 grade)

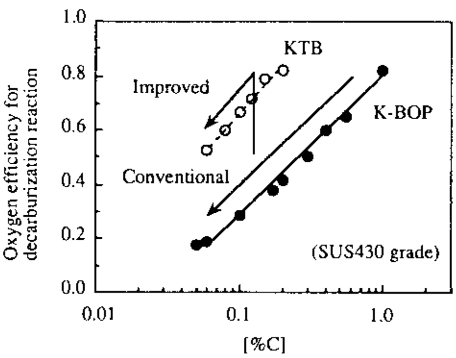

Fig. 6 Relationship between carbon content in molten steel and oxygen efficiency for decarburization reaction (SUS430 grade)

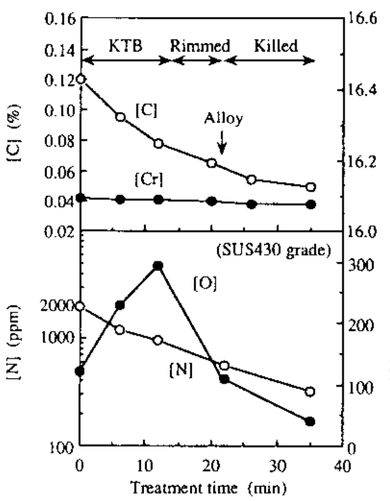

Fig. 7 Change in chemical composition during RH treatment (SUS430 grade)

decarburization process incorporating oxygen-supplied decarburization in a vacuum by the KTB method, the decarburization function was distributed over the K-BOP and KTB, making it possible to increase the total oxygen efficiency for decarburization and thereby achieve rational decarburization of stainless steel.

Figure 7 shows the compositional behavior of SUS430 during KTB treatment; **Fig. 8** presents a comparison of the oxygen balance during decarburization to the low carbon content region with the K-BOP and KTB. These results indicate that, with the KTB treatment in the K-BOP−KTB process, Cr oxidation loss is virtually eliminated and it is possible to decarburize to product target compositional values. Further, with the adoption of this composite refining process, Cr oxidation loss in the K-BOP has been reduced, as shown in **Fig. 9**, because it is possible to tap the K-BOP in the middle carbon content region.

4.2 Optimization of KTB Operation

Because N_2-diluted decarburization is conducted in the decarburization furnace without using Ar gas with steel grades such as SUS304 which have loose [N] specifications, the [N] content of the steel at the start of RH degassing treatment reaches substantially the saturation concentration under the pressure of $P_{N_2} = 1$. **Figure 10** shows changes in [N] during the RH degassing of SUS304. A rapid denitrification reaction proceeds

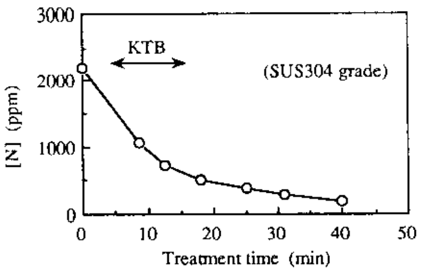

Fig. 10 Change in nitrogen content during RH treatment (SUS304 grade)

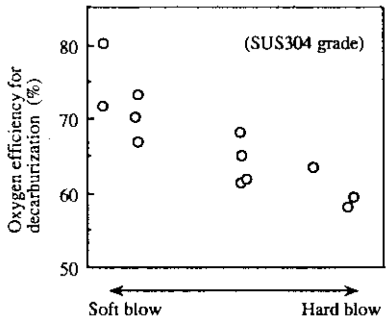

Fig. 11 Effect of blowing condition on oxygen efficiency for decarburization (SUS304 grade)

together with the decarburization reaction which is in progress while oxygen is supplied by the KTB in the first stage of RH degassing treatment, and as a result, the phenomenon of foaming of the molten steel in the vessel can be observed. Decarburization behavior was investigated under these conditions by varying the height of the KTB lance and the oxygen rate. The results are shown in **Fig. 11**, which indicates that oxygen efficiency for decarburization is improved by adopting a "soft blow" condition for top oxygen blowing. Thus, in this type of decarburization furnace, with steel grades produced using N_2-oxygen decarburization, the oxygen supply rate is reduced within the range where it will not decrease the rate of decarburization, and the lance height is increased and decarburization is conducted in the direction of soft blowing.

4.3 Effective Use of KTB

With conventional RH degassers, skull frequently adheres to the interior of the vessel as a result of splashing of the molten steel, leading to unacceptable product compositions as a result of contamination by skull dropping into the bath, and to blockage of the vessel and other problems related to the accumulation of skull. Introduction of the KTB equipment and the beginning of top oxygen blowing oxygen-supplied decarburization has reduced the amount of skull metal adhering to the vessel interior by promoting post-combustion in the vessel. Because it is desirable to further reduce the amount of skull adhering to the vessel interior, tests have recently concluded in which oxygen was supplied at the lance holding position during treatment after the completion of oxygen-supplied decarburization, which melted the skull in the vicinity of the lance opening, and skull in the upper part of the vessel was melted during treatment using a special purpose jig, reducing the skull adhering to the interior of the tank to a negligible level. As a result, operational problems due to skull have been eliminated and product quality has shown a marked improvement.

5 Establishment of Production Technology for Specialty Stainless Steels

5.1 Refining of SUS447J$_1$ (30Cr-2Mo) by K-BOP–SS-VOD Process

Because super-ferritic stainless steel SUS447J$_1$ (30Cr-2Mo) of the composition shown in **Table 4** possesses extremely high corrosion resistance and is not susceptible to stress corrosion cracking, demand for this grade should show a dramatic increase in coming years. Moreover, it is also beginning to attract attention as an atmospheric corrosion resisting steel for exterior applications, and has recently been adopted as a roofing material at the New Kansai Airport.

Table 4 An example of typical chemical composition of 30%Cr-2%Mo steel (SUS447J$_1$) (%)

C	Cr	Mo	N
0.0020	30.0	2.0	0.0070

In order to secure the material properties of this steel grade, it is essential to minimize the values of [C] and [N], which are interstitial impurity elements. A number of reports have appeared in the past in connection with the decarburization and denitrification behavior of high-Cr steel,[9,10] and this company has achieved high levels of purity with the SS-VOD, which makes possible strong stirring under a vacuum.

The production route for this steel grade at Chiba Works was originally the MF–SS-VOD process, but since the shutdown of the melting furnace following the establishment of the smelting reduction process for Cr ore, production has shifted to the K-BOP–SS-VOD process. It is difficult to refine steels having both high contents of [Cr] and [Mo] and ultra-low contents of [C] and [N], which had entailed the problems of an extremely long refining time and a consequent reduction in productivity, but considerable improvement has been achieved in this area in recent years.

In the K-BOP, as shown in **Fig. 12**, it is necessary to melt basically the same amount of ferroalloy with the dephosphorized hot metal. The key points during blowing are therefore to avoid leaving any unmelted material and to determine the amount of decarburization. **Figure**

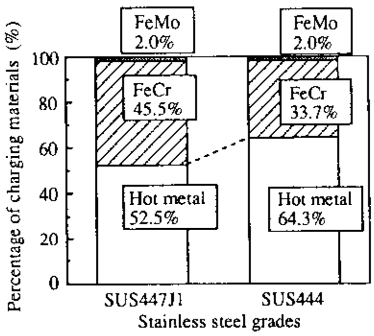

Fig. 12 Comparison of charging materials between SUS447J_1 and SUS444

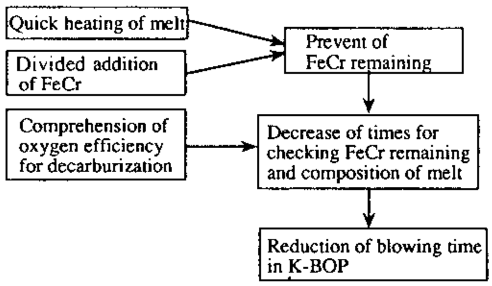

Fig. 13 Concept for reduction of blowing time in K-BOP

13 shows the concept employed to reduce the blowing time in the K-BOP. Although FeSi is used to heat the bath to the temperature required to melt FeCr, bath heating in the initial stage of refining is considered necessary in order to achieve a rapid completion of melting. The addition of a variety of ferroalloys was therefore studied, but in the pattern adopted, FeSi is added in one lot in the initial stage, and FeCr is added in divided lots during blowing. In addition, the oxygen supply rate has been increased, and the amount of decarburization is now estimated using off-gas data. As a result of these improvements, the K-BOP blowing time has been shortened by about 70 min from that when the K-BOP—SS-VOD process was first introduced, and it is now possible to complete blowing within 80 min as shown in **Fig. 14**. Moreover, with improvements in blowing techniques for the K-BOP, the hit rate for tapped-steel composition targets has also improved, and it has become possible to reduce the [C] content at the start of treatment. The temperature measurement/sampling method has also been changed from the conventional bomb type to a probe type, reducing the time until samples are sent. Consequently, as shown in **Fig. 15**, the SS-VOD treatment time has been reduced by approximately 50 min from that originally required, and stable treatment in under 180 min has been realized.

Because it was possible to achieve a broad reduction in the time required in the refining stage, as described above, an impediment to productivity has been eliminated and it has become possible to produce steel in mass quantities.

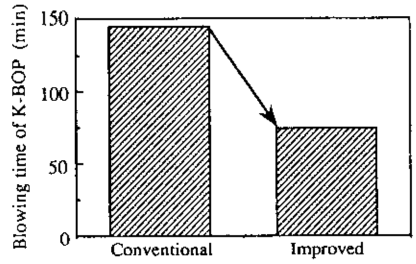

Fig. 14 Comparison of K-BOP blowing time between conventional and improved methods

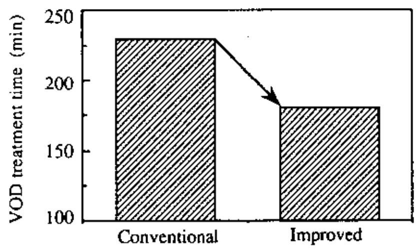

Fig. 15 Comparison of VOD treatment time between conventional and improved method

5.2 Establishment of Continuous Casting Technique for 20%Cr-5%Al Steel

Stainless steel with a composition of 20%Cr–5%Al serves as the basic material for the metal honeycomb of catalytic converters used to remove pollutants from automotive exhaust gas. Because metal honeycombs improve engine efficiency and offer other advantages over conventional ceramic honeycombs, this steel grade is expected to see great quantitative expansion in the future.

The composition of this steel grade is shown in **Table 5**. As distinctive features, in addition to containing 5% aluminum, a 0.08% addition of La is made in order to enhance oxidation resistance. Moreover, to avoid a decrease in oxidation resistance and the toughness of the material, and ultra-low carbon, ultra-low nitrogen composition is used, and 0.07% Ti is added to fix [C] and [N].

Where the production route is concerned, the K-BOP—SS-VOD process was adopted because this is an ultra-low carbon, ultra-low nitrogen steel, and a trial of casting was made using the continuous casting method.

Table 5 An example of typical chemical composition of 20%Cr-5%Al steel (%)

Cr	Al	Ti	La
20.0	5.0	0.07	0.08

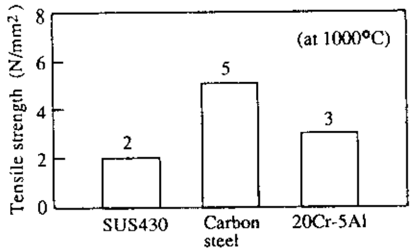

Fig. 16 Comparison of tensile strength at high temperature

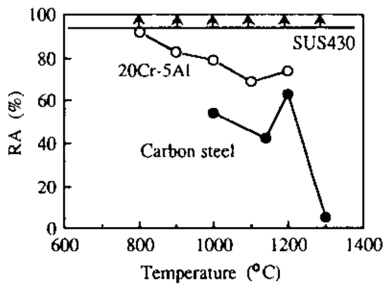

Fig. 17 Comparison of reduction of area at high temperature

The results of measurements of the liquidus temperature, solidus temperature, and heat transfer ratio of this steel grade, which were necessary in determining the continuous casting conditions, indicated that it would be possible to use basically the same conditions as those for conventional ferritic stainless steel. The results of measurements of high-temperature tensile strength are shown in **Fig. 16**, and again were substantially the same as those for conventional ferritic stainless steel, in spite of the fact that this index of strength is lower than with high-carbon steel. **Figure 17** shows a comparison of reduction in area (RA). Because the RA of this grade was higher than that of carbon steel, at more than 60%, and there was no fear of surface cracks, an intensive secondary cooling at upper part of strand was adopted in consideration of bulging between the rolls.

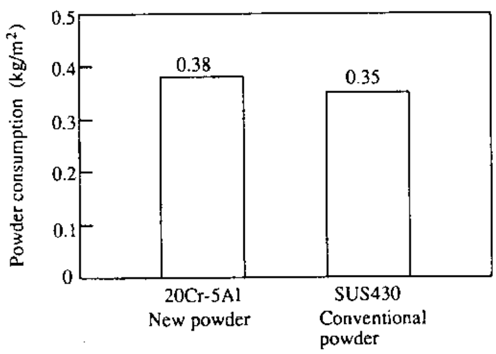

Fig. 18 Comparison of powder consumption between 20%Cr-5%Al steel and SUS430

The Al_2O_3 content of the mold powder was enriched, and the problem of deterioration in the physical properties of the powder was solved by major changes in the composition of the powder. **Figure 18** shows powder consumption in comparison with that with conventional SUS430. Powder consumption was virtually the same as with conventional SUS430, and stable production was possible by maintaining a molten layer 15–30 mm in thickness.

These results are considered to form the basis for the establishment of a mass production system capable of responding to future growth in demand.

6 Conclusions

The stainless steel production process at Kawasaki Steel in recent years is summarized as follows:

(1) At the smelting reduction furnace, operational conditions have been established which make it possible to increase the amount of heat generated by post-combustion in the vessel, and thus to increase the Cr pellet feed rate.
(2) Rational decarburization has been established by the introduction of a composite decarburization process using the K-BOP and KTB.
(3) Stable production techniques have been established for specialty stainless steels such as 30%Cr-2%Mo and 20%Cr-5%Al steel.

Active promotion of these technical developments has made it possible to select the most appropriate production process for steel grades, and has resulted in the realization of a stable, high-productivity system for stainless steel production which responds to increasingly strict quality requirements for stainless steel.

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