KAWASAKI STEEL TECHNICAL REPORT
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Recent Activities in Research of Steelmaking

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The last decade activities in steelmaking research laboratory at Kawasaki Steel have been described. The main activities were concentrated on high productivity, high quality, and cost reduction process to compete with the world wide market. The following newly developed technology has been also discussed: high efficient production method for ultra low carbon steel, Cr ore smelting reduction method in top and bottom blowing converter, the new electromagnetic brake for the molten steel in the mold (FC mold), separation of inclusions from molten steel in tundish (CF T/D) and continuous forging process.

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1 Introduction

The steelmaking process is important for determining the quality and cost of products. With the properties of steel products requested by customers growing in sophistication, the requirements for the steelmaking process are also becoming more advanced and diversified. Looking back on the past 30 years of steelmaking, we find that in the first 20 years, the converter process and CC process were introduced in the refining and casting processes the optimization of these two processes resulted in a great increase in the production, yield and productivity of crude steel in this age. On the other hand, it can be said that the past decade was an age when the steelmaking process was brought nearer to completion in order to meet the requirement for improvement in the quality of steel products after the establishment of the converter and CC methods. The establishment of techniques for the mass production of high-quality inexpensive ultra low-C steels, mainly for use in automotive steel sheets, may be the most typical example.[1-4] At Kawasaki Steel, the installation of the No. 4 RH equipment and No. 4 CC equipment at Mizushima Works and expansion of the No. 3 RH equipment at Chiba Works have been carried out in the past ten years to produce high-quality steels.

It can also be said that the past decade has been an age when demand for stainless steels increased while quality requirements for stainless steels became severer. To meet these requirements, the No. 4 steelmaking plant devoted solely to the production of stainless steels was constructed at Chiba Works.

In the steelmaking laboratory, research activities have been put into developing and introducing new technologies in order to realize super clean steels and cost reduction in the construction of the above mentioned new plant.

This paper describes principal technologies developed in the refining and CC fields.

2 Outline of Developed Principal Technologies

2.1 Promotion of Decarburization of Ultra Low-Carbon Steels

It became necessary to develop mass production technologies for ultra low-C steels with [C] < 10–15 ppm, excellent in formability especially for use in automotive steel sheets. Therefore, a technology for high-rate decarburization in an ultra low-C concentration region in RH was developed.

It is considered that a decrease in the decarburization rate in an ultra low-C concentration region in RH is caused by a decrease in the gas-liquid interfacial surface area due to a decrease in CO boiling in the vacuum vessel[5]. Therefore, a new refining technology was devel-

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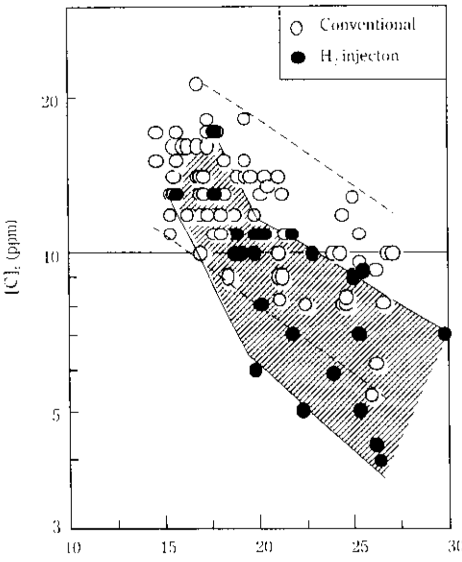

Fig. 1 Relation between final [C] and decarburization treatment time in H_2 injection method and conventional method

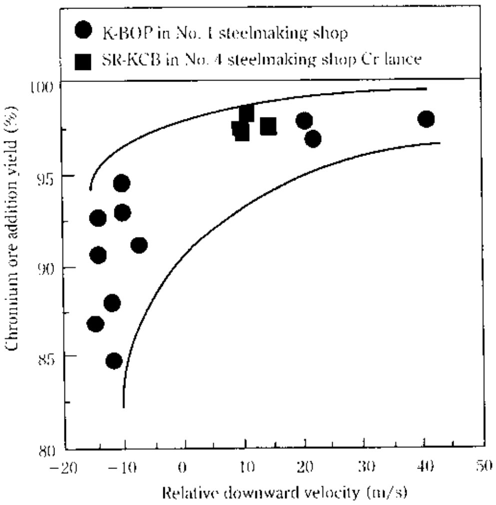

Fig. 2 Relation between chromium ore addition yield and relative downward velocity calculated as the difference between downward velocity of chromium ore and that of gas

oped to raise the decarburization rate, which involves injecting and dissolving a large volume of hydrogen gas as the circulation gas in molten steel, thereby keeping the driving force for generating bubbles in the vacuum vessel even in an ultra low-C concentration region where CO boiling usualy decrease.[6] It is possible to raise [H] up to almost 3 ppm by injecting 3 to 4 Nm^3/min of hydrogen gas. This has enabled the decarburization rate constant at [C] of 20–10 ppm to increase from 0.05 min^{-1} to 0.1 min^{-1} and hence achieve a minimum [C] of 4 ppm. As shown in **Fig. 1**, it has become possible to refine steels with $[C] \leqq 10$ ppm in a relatively short treatment time without increasing the snorkel diameter.

2.2 Stainless Steel Manufacturing Method by Smelting Reduction of Chromium Ore[7]

In the No. 1 steelmaking plant, the smelting reduction process based on the dual use of top and bottom blown converters (K-BOP) has been used since 1985. In this case, smelting reduction has been performed using prereducted Cr ore pellets as the raw meterial in order to perform short-time treatment within the casting time of sequential continuous casting. At the No. 4 steelmaking plant, an investigation was carried out on a new smelting reduction furnace that directly reduces Cr ores with a minimum use of ferrochromium, which consumes a large amount of electrical power.

Most of the Cr ore mined in the world is in sandy form and there is apprehension that losses due to the flying of sandy ores into the exhaust gas system of the furnace may occur. Therefore, an experiment on the Cr ore addition was conducted beforehand in the No. 1 steelmaking plant and the advantages and disadvantages of various addition methods were compared. As a result, it was ascertained that direct addition of Cr ores to the furnace via a lance is favorable for Cr ore addition with a high yield. Furthermore, a numerical analysis of the gas flow in the converter was conducted with the aid of the fluid analysis program "PHENICS" which revealed that, as shown in **Fig. 2**, the ore addition efficiency can be determined by the relative downward velocity (gravitational velocity of ore − upward gas velocity in the furnace). Therefore, direct Cr ore addition to near the furnace center, where a downward flow generates, is an appropriate method.

Based on the above results of the experiment and numerical analysis, a lance dedicated solely to the charging of Cr ores was adopted in the new steelmaking plant. The Cr ore charging lance, which can move independently of the top-blowing lance, descends only in the smelting reduction period to add Cr ores.

The equipment of the new steelmaking plant was also designed to permit the use of a large amount of stainless steel scrap.

2.3 Decarburization of Stainless Steel by a Combination of Top and Bottom Blown Converter and VOD Process[8]

In the low carbon concentration region of [C] < 1.0%, it is necessary to control the temperature to a narrow range of about 1 700°C in order to prevent the erosion of refractories and suppress the oxidation of Cr. At Kawasaki Steel, a technique for blowing N_2 from a top lance in the final stage of refining (the top-blown N_2 process) has been developed to suppress a rise in the molten steel temperature and reduce the oxidation of Cr.

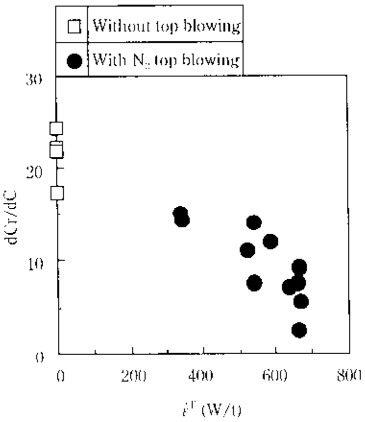

Fig. 3 Effect of N_2 blowing method with top lance in the final stage of decarburization in DC-KCB ($\dot{\varepsilon}^T$: Stirring energy by top blowing N_2 (W/t))

The oxidation of Cr can be suppressed by top-blowing N_2 in the final stage of refining.

The relationship between the amount of oxidation of chromium in the low-C concentration region and the stirring energy of top-blown N_2 is shown in **Fig. 3**. In the top-blown N_2 process, the oxidation of Cr is decreased not only by an increase in the N_2 flow rate, but also by a hard blow with lowering a lance height. The effect of the top-blown N_2 process is thought to be due to the promotion of the slag-metal mixing behaviour by the increase in the stirring energy at the slag-metal interface. Furthermore, it has become possible to make the treatment time using the decarburizing furnace (DC-KCB) equal with the VOD treatment time, and to minimize the oxidation of Cr by adopting a combination decarburization process. The total treatment time in the decarburizing furnace and the VOD should be minimumized for high productivity. The above steelmaking plant exclusively for the manufacture of stainless steels was brought into operation in July 1994 and has contributed to the efficient refining of stainless steels in line with the company's strategy of principal raw materials.

2.4 Flow Control of Molten Steel in Mold by FC Mold[9)]

The electromagnetic brake (EMBR), developed to improve the internal quality of cast products and productivity of curved-mold type continuous casters has helped in stabilizing the meniscus and reducing internal inclusions. However, there has been a limit to an increase in the casting speed with the use of the EMBR.

Therefore, the FC mold (flow control mold) was developed as a second-generation electromagnetic brake for high-speed casting by improving the weak points of the first-generation electromagnetic brake developed based on curved-mold type continuous casters. The FC mold is constructed in such a manner that magnetic fields, which are uniform throughout the wide face of the mold, are arranged at the meniscus and in the bottom part of the mold, as shown in **Fig. 4**. In the conventional EMBR, the flow of molten steel is dispersed by braking the discharge flow from the nozzle. The FC mold was improved so that the flow from the nozzle is confined between the upper and lower magnetic fields.

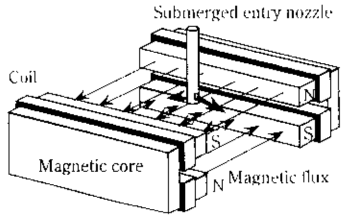

Fig. 4 Schematic illustration of the FC mold

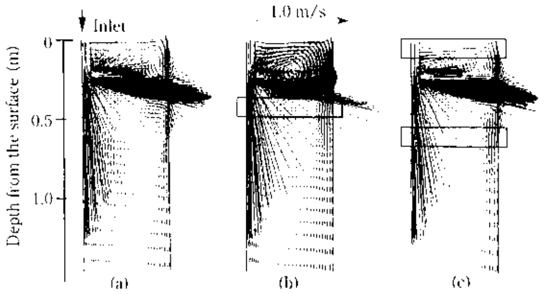

Fig. 5 Calculated velocity patterns of liquid flow in the centerline section of a mold: (a) without magnetic field, (b) with 1 pair of magnetic poles, (c) 2 pairs of magnetic poles (FC mold)

The flow patterns analyzed in half of the thickness are shown in **Fig. 5**. In the figure, pattern (a) is the case of no magnetic field, pattern (b) is a one-stage application of magnetic fields, and pattern (c) is a two-stage application of magnetic fields. In both patterns (b) and (c), in which magnetic fields are applied, the downward flow velocity in the bottom part of the mold is suppressed compared with (a), in which no magnetic field is applied. Furthermore, it is apparent that the flow velocity near the surface is lowered by the two-stage magnetic fields in (c) compared to the case of one-stage application of magnetic fields in (b).

The upper magnetic field applied at the meniscus reduces the horizontal flow velocity of the surface of molten steel and stabilizes the surface waves at the meniscus, thus substantially decreasing the fluctuations of the meniscus level. At the same time, the lower magnetic field applied to the bottom part of the mold reduces the downward flow velocity along the narrow-face shell, thus making a plug flow. The control of the flow in the mold by this two-stage application of magnetic fields reduces the mold powder entrapment at the meniscus level and suppresses the entry of large inclusions and

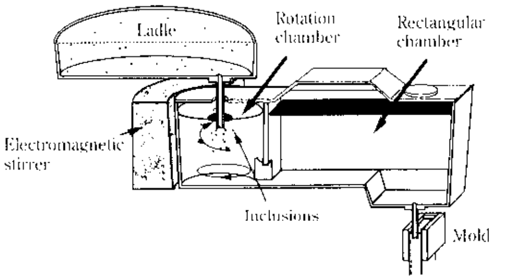

Fig. 6 Schematic illustration of the centrifugal flow tundish (CF tundish)

bubbles into the interior of the slab.

When the FC mold is not used in the manufacture of ultra low-C automotive steel sheets, the incidence of surface defects increases abruptly at casting speeds exceeding 1.7 m/min. On the other hand, when the FC mold is used, the incidence of surface defects is less than half of the conventional level irrespective of the casting speed. Furthermore, the magnaflux index of tinplates for cans decreases to less than half the conventional level due to the application of magnetic fields in the FC mold, thus substantially improving the internal quality of slabs.

The FC mold is presently incorporated in the regular process in the No. 4 CC equipment at Mizushima Works and the No. 3 CC equipment at Chiba Works, contributing to an improvement in the surface and internal quality of slabs.

2.5 Centrifugal Flow Tundish

The centrifugal flow (CF) tundish has been incorporated in the regular manufacturing process of Al-killed stainless steels, to help increase the cleanness of steel products. The concept of the CF tundish is shown in **Fig. 6.**[10] The molten steel suply side of the tundish is formed in cylindrical shape (this is the separation space of nonmetallic inclusions) and a rotational electromagnetic force is applied using a linear motor to molten steel to produce a horizontal rotational flow. Inclusions that have a smaller specific gravity than molten steel are floated up and removed in the central zone of the separation space. The coalescence and coagulation of inclusions are promoted by a turbulent flow due to this horizontal rotational flow, and the vertical flow changes due to the horizontal rotational flow, suppressing the short-circuit flow between the ladle and the mold. As a result, slag separation in the ladle exchange period is promoted.

Owing to the above mechanism, the CF tundish has a large deoxidation rate constant of not less than 0.5 min^{-1} and a deoxidation capacity larger than that of an RH degasser, i.e., 0.1 to 0.2 min^{-1}.[11] As a result, the total oxygen value in the tundish is 5–10 ppm in the Al-killed steels. Steel sheets with excellent surface properties can be produced without the occurrence of nozzle clogging.

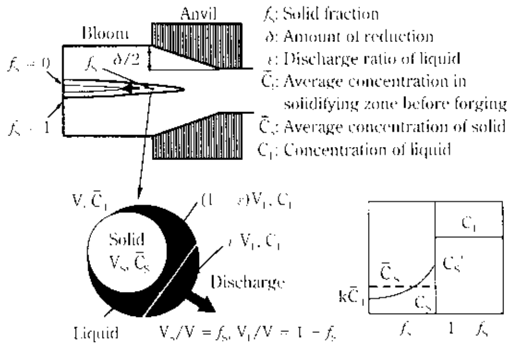

Fig. 7 Schematic drawing of segregation model

2.6 Control of Centerline Segregation of Blooms by Continuous Forging

In the CC process, center-line segregation is an essential defect. In the case of continuous casting of blooms, the segregation degree of solute elements in the center portion of the cast bloom is particularly significant due to the small cross-sectional area of final solidification. High-C steels for bearings, piano wires, tire cords, etc., have large absolute amounts of solute elements and they are often heat treated during their manufacturing processes. In these steels, carbon segregation induces uneven martensite transformation thus posing a major problem to final products.

Continuous forging is a process in which large amounts of compressive deformation are continuously applied at the final stage of solidification.[12] In this process, forging dies with an appropriate taper, which move reciprocally in synchronized with casting motions, are used to press the steel bloom.

Continuous forging has a great feature that the extent of center-line segregation can be freely controlled, permitting negative segregation in the central zone of the separation space, depending on the use of products. The negative segregation is considered to be caused by the discharge of residual, solute enriched liquid into the upper strand. The segregation model is shown in **Fig. 7**.

Assuming that the residual liquid is continuously discharged at the discharge ratio ε, the average concentration of the liquid phase at the solid fraction f_S can be calculated by the micro-segregation theory of Brody and Flemings[13] and the average concentration of the solid phase can be determined from a material balance. The segregation ratio K_c determined from these concentration models was in good agreement with the measured value. A comparison between the calculated value and the measured value indicated that the higher the solid fraction during pressing by forging, the lower the discharge ratio of liquid. Therefore, it has become possible to vary the concentrations of solute elements in the center portion of the bloom by controlling the solid fraction in the central zone during continuous forging. The frequency of rupture at drawing of high-C wire was substantially improved by controlling the centerline segregation to the negative segregation side on the basis of this principle.

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