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Change and Development of Continuous Casting Technology

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Abstract

It was 60 years ago that continuous casting (CC) of steel was introduced to Japan. The first continuous caster of Japan was commissioned in 1955, and in the 1970s, the basic technology for the equipment and operation of the process was firmly rooted in the country. Today, after 40 years, the CC ratio of the country exceeds 98%; the ratio of Nippon Steel Corporation reached 100% in 2007. In the meantime, the CC technology advanced, aiming at high-speed casting of high-quality steel to meet the demand for widely varied products of increasingly severe specifications. This paper describes the history and present state of the CC technology of the company, and some future prospects.

1. Introduction (Historical of Continuous Casting in Japan)

In 1994, the 351st issue of Shinnittetsu Giho described the change in the continuous casting (CC) technology from the 1960s to the 1990s.[1)] According to the article, the history of CC in Japan is divided as follows: 1st period (1960s) of rooting CC as an industrial process; 2nd period (1970s) of technical advance and machine size expansion; 3rd period (1980s) of technical maturity; and 4th period (1990s) of early development of new CC methods. The CC technology as we see today was firmly established by then.

Continuous casting, presently responsible for over 98% of Japan's steel production, can be viewed as an industrially mature production process. More than 15 continuous casters were newly built and nearly 30 revamped in the 1990s and thereafter. Over the last 20 years, especially, the development of CC technology focused on productivity enhancement, operation stabilization, and improvement in quality capacity to incorporate intended quality in products.

2. Change of World Crude Steel Production

From the petroleum crisis in 1973 - 2000, the crude steel production of the world stayed within the range of 700 - 800 million tons per annum (unless otherwise specified, all the units herein are metric), but thereafter, owing largely to the rapid growth of China and other developing economies, it increased quickly to exceed 1,400 million tons per annum in 2010. **Fig. 1** shows the change in crude steel production of principal countries and the world total. After the disintegration of USSR, Japan was the largest steel producing country of the world for four years from 1992 to 1995, but because of its

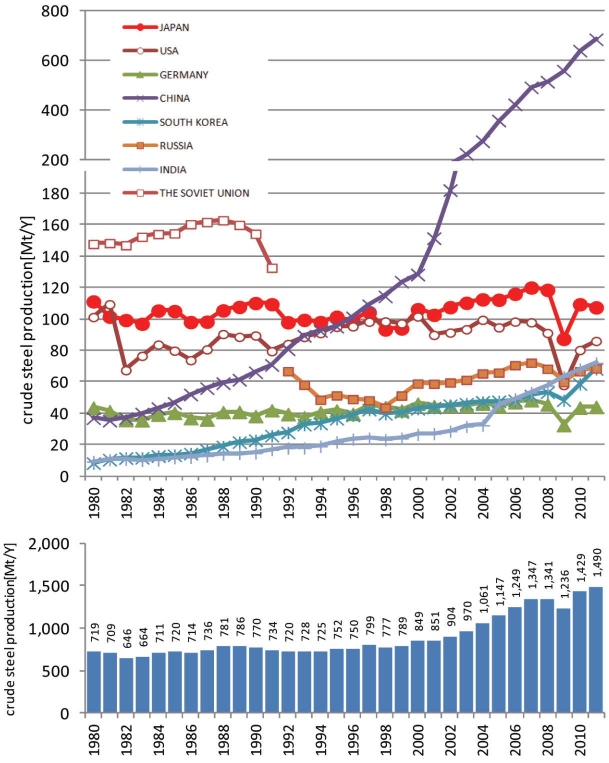

Fig. 1 Crude steel production of major countries and world total (source: World Steel Association)

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Table 1 Specifications of Nippon Steel's principal slab casters

	Yawata 2st	Yawata 3st	Nagoya No.1CC	Nagoya No.2CC	Kimitsu No.2CC	Kimitsu No.3CC	Kimitsu No.6CC	Oita No.4CC	Oita No.5CC
Type	VB	VB	VB	VB	VB	VB	VB	VB	VB
Strand	1	1	2	2	2	2	1	2	2
Machine radius (m)	7.55	7.73	7.7	9.5	9	9	10	7.5	7.5
Metallurgical length (m)	38.7	31.7	35.8	48.4	34.26	42.96	41.2	44.5	44.5
Start-up	1979.04	1982.12	1970.11	1980.11	1980.03	1982.01	2006.11	1976.03	1976.08
Revamping [VB]	2005.08	1991.12	2000.03	1990.09	-	-	-	1995.07	1998.04
Revamping [metallurgical length extension]	-	-	2007.04	-	-	1996.03	-	-	-
Tundish shape	Boat	Triangle	H-shape	H-shape	Boat	Boat	Boat	Boat	Boat
Tundish capacity (t)	30	23	45	60	60	60	60	70	70
Casting thickness (mm)	250	250	250	250	240(300)	240	240,300	282	282
Width range (mm)	650-1900	960-1650	900-2150	900-1630	980-2300	700-2050	980-2300	1100-2150	1100-2150
Vertical length (m)	2.5	2.5	2.16	2.26	2.5	2.5	2.7	2.5	2.5

rapid growth, China took over the position in 1996, and in 2010, the country is responsible for no less than about a half of the world steel production.

Over the last 10 years, the crude steel production of China has increased by approximately 50 million tons or more per year on average, which means that five to six new steel works of the size of Nippon Steel Corporation's Kimitsu Works were built every year. Presently, Japan is second in the world in terms of crude steel production (as of 2010), but other developing economies are closely behind. Although it is difficult for the Japanese steel industry to return to the top position in quantitative terms, in order to maintain its superiority over the steel industries of the growing economies, it is imperative for the industry to continue developing technology to incorporate desired quality in products at each steelmaking process as well as enhance integrated quality control.

3. Change in Technical Backgrounds

While the world steel demand has grown over the last 20 years because of the rapid economic expansion of developing countries, the steel demand inside Japan has remained substantially at the same level, and so has been the steel production. Instead, in view of the increased interest in energy saving and higher quality of manufactured goods, the steelmakers of Japan have shifted focus to high-efficiency production of high-quality products over the period.

In 2005, Nippon Steel Corporation organized inter-works working groups in the fields of steel refining and CC, which have acted expeditiously to accelerate problem solving and further enhance the level of steelmaking technologies. At present, the working groups encompass Steelmaking R&D Division and R&D Laboratories of all the works of the company to deepen the overall technical capability of the steelmaking divisions across the company.

4. Productivity Enhancement

Needless to say, the means to increase CC production include improving machine throughput (t/h) and net working ratio. Measures have been taken to improve these items at different steel works in consideration of their production structures. Significant results have been achieved, especially at the works where CC constituted the bottle neck in the vertically integrated production route.

Only one slab caster, Kimitsu No. 6 CC, was newly commissioned in the last 20 years. The production increase and quality improvement of all other casters were accomplished through revamping and operation improvement. **Table 1** shows the present states of the principal slab casters of the company.

4.1 Increasing throughput

4.1.1 Increase in casting speed

Extending the machine length is an effective measure to increase the casting speed of a continuous caster. No. 1 CC of Nagoya Works, a curved-mold machine, was modified into a vertical-and-bending (VB) machine in 2000, and on that occasion, two segments were added to its horizontal portion, extending the machine length from 26.9 to 32.0 m.

As a result, productivity was increased, and in addition, quality capacity was enhanced to improve the quality of tinplate steels for food cans, which undergo heavy working and are sensitive to inclusions, blowhole-sensitive steels such as interstitial-free (IF) steels widely applied to the outer panels of automotive bodies, and high-strength steels. As a consequence, the share of functions was clearly defined between Nos. 1 and 2 CCs in the same plant building. Later, in 2007, the machine length of No. 1 CC was extended further to 35.8 m as the converter capacity was increased. The dummy bar of Nagoya No. 1 CC, of an upward-inserting type, was made shorter, and its storage method was changed (**Fig. 2**).

4.1.2 Increase in cast section

The mass-produced steels for hot bands and heavy plates of Oita Works were cast mainly through Nos. 4 and 5 CCs, both of a

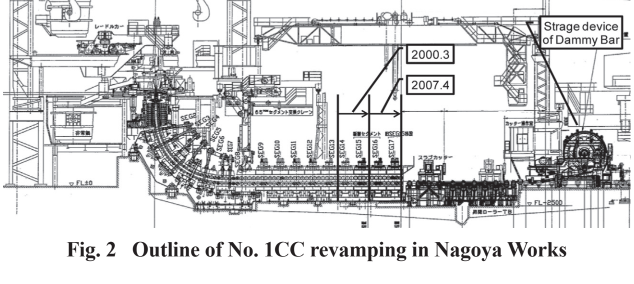

Fig. 2 Outline of No. 1CC revamping in Nagoya Works

curved-mold type. To enhance the quality of steels subject to strict control of inclusions, and in consideration of the ease of production scheduling between the casters, No. 5 CC was modified into a 2-strand, vertical-and-bending machine in 1991, and No. 4 CC likewise in 1995. The slabs from these two casters go to a breakdown mill, called the sizing mill, to reduce the width and thickness; this process, called the Direct Link Process V, was built in 1980. Making the most of the large-section, constant-size casting by the process, the average casting width and thickness of the casters were increased in several steps.

As a result, Nos. 1, 4, and 5 CCs of Oita recorded a total monthly production of 901,000 t in 2010, No. 4 CC hit a monthly production record of 421,800 t in July 2011, and No. 5 CC another of 425,100 t in August the same year.

When it is necessary to minimize internal and surface defects, the casting speed is lowered (to allow impurities to float to the meniscus in the mold), and in the case where the machine length is more than enough for complete solidification at such a slow speed, slab thickness is increased to increase production. This method has been commercially used at Nagoya and Oita Works.

4.2 Measures to increase net working ratio

Increasing working time and casting time is also effective at increasing the production of continuous casters. In relation to continuous casters, these terms are defined as follows:

calendar time = net working time + down time; and
net working time = casting time + preparation time.

The keys to higher production capacity are how to decrease down time to increase the ratio of net working time to calendar time and how to decrease preparation time to raise the ratio of casting time.

4.2.1 Stabilizing initial solidification

Break-out (BO) is one of the operation troubles that most adversely affect the production of continuous casters. It occurs as follows. During the initial solidification of molten steel in a CC mold, the solidification shell may not form adequately at some position for whatever reason, and when that position comes out of the lower end of the mold, molten steel flows out through the defective part of the shell. BO does not merely decrease production, but inflicts heavy damage to the equipment, calling for intensive repair work. To prevent BO, therefore, it is essential to make sound initial solidification shells form stably in the mold.

The principal factors that affect the initial solidification of steel in a CC mold are steel temperature, mold powder (flux), mold copper plates, and primary cooling water.

Various improvements and modifications of mold powder have been conducted so that it liquefies and gets between the initial solidification shells and the copper plates evenly and stably, even at high casting speeds, and thus serves for homogeneous heat removal and lubrication. While there were some reports on the mechanism of hydrogen-induced BO,2) the mechanism of BO of silicon-killed steel remained unclear. Later, the mechanism was finally clarified,3) and the occurrence of this type of BO has been decreased by use of high-basicity powder.

The copper plates on the mold surfaces are cooled by water from the back side, thus removing heat from the steel to accelerate its solidification. Since the shells contract as the solidification advances, the copper plates, especially those on the mold short faces that contact slab sides, are tapered downward to ensure the contact areas. However, because the contraction does not progress linearly, if the copper plates are dead flat, gaps are likely to form between the plates and shells, heat is not removed well there, and the solidification becomes uneven, possibly leading to BO. As a countermeasure, a multistep tapered mold was proposed and commercially applied,4) wherein copper plates on the short sides are tapered in different angles according to the contraction of the shell; it proved effective at dissolving the problem of uneven solidification and preventing the BO due to the cause. Besides the above, in-mold magnetic stirrers (named M-EMS), which control the steel flow in a mold to make the steel temperature homogeneous at the meniscus and thus make the shell thickness even (to be explained later), have been effectively used for commercial production.5, 6)

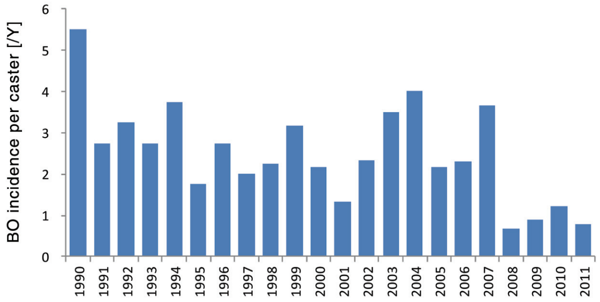

Fig. 3 Average incidence of BO per caster (casters listed in Table 1)

As a result of the above measures to stabilize the initial solidification of steel, the incidence of BO of Nippon Steel Corporation's continuous casters decreased significantly, as seen in **Fig. 3**.

4.2.2 Optimum relationship between steel temperature and casting speed

What is essential for increasing CC production on the basis of stable initial solidification is maintaining an adequate balance of the steel temperature in the mold, heat removal, and casting speed. When both steel temperature and casting speed are high, the solidification shell does not develop sufficiently, and there may be a case where molten steel breaks through the shell immediately below the mold (remelting BO). This indicates that, to increase production without BO, the steel temperature and casting speed must be controlled adequately.

Casting temperature is one of the most important control parameters; it is defined on the basis of solidification temperature according to the steel chemistry and dictates retroactively the end point temperature of the secondary refining and the tapping temperature from the converter. For adequate control of casting temperature, induction heaters, plasma heaters, and other heating devices have been provided for tundishes.

On the other hand, an excessively slow casting speed at a period of high steel temperature, such as at the middle of a charge, causes a loss of production. Steel temperature is measured at different positions in different casters and the throughput is also different; therefore, each continuous caster had its own standard temperature–speed table that defined the relationship between casting temperature and maximum casting speed on the basis of past experience and the calculation method of each work.

The working group for CC re-examined the steel solidification in the mold using the solidification simulation models developed by Plant Engineering & Facilities Management Center (PFC), and accordingly revised the temperature-casting speed tables of all casters of the company. This made it possible to increase the average casting speed without causing remelting BO due to insufficient shell development (**Fig. 4**).

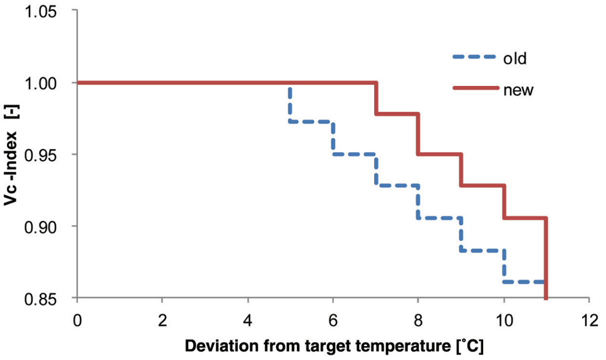

Fig. 4 Example of revision of temperature-casting speed table

4.2.3 Break-out prediction

How to predict and prevent the occurrence of BO: technology whereby thermocouples are embedded in a mold to continuously monitor the temperature of the copper plate surfaces and to detect insufficient initial solidification, or the occurrence of BO, has since long been given, and if such solidification is detected while the thermocouple is still within the mold, casting speed is decreased to prevent the position from passing to the lower end of the mold, thus preventing the occurrence of a BO.

However, the time allowance for the deceleration became limited because of higher casting speed of the latest operation practice to increase productivity, and the initial solidification behavior changed owing to the change in the kind of steel produced. It became, therefore, necessary to review the technology for initial solidification control and prediction of BO.

Another problem lately is that, because of the scarce incidence of BO and generation change of casting operators, few operators have the experience of actually dealing with BO, and should one occur, they may fail to take adequate measures immediately and allow the damage to spread.

On the other hand, because of the rapid advance in computer technology, it is now possible to process considerable information from many thermocouples in a sophisticated manner, and visualize and display the situation on monitoring screens near operators' positions. Accordingly, by combining information from thermocouples with solidification calculation, a system is being developed to detect any abnormal formation of initial solidification shells and to notify it to the operators before the BO occurs. These developments will be mentioned later.

What is important for continuous casters that frequently change the cast width during high-speed casting is the control of the side shifting and taper angles of the mold short faces. Slab cooling at the edge rolls immediately below the mold also poses a problem. Efforts have been made to enhance the operation control according to characteristics peculiar to individual casters under different casting conditions. Nippon Steel Corporation is developing an improved method for measuring the mold taper and a precision positioning system for the mold short faces that can replace the conventional stepping cylinder mechanism.

Thus, the company is looking for effective measures to prevent BO, one of the most long-standing and toughest problems of continuous casting.

4.3 Extension of shutdown intervals and prevention of operation troubles (increasing operating ratio)

To prevent machine troubles such as breakage of segment rolls and bearings, Nippon Steel Corporation's continuous casters undergo periodical shutdown for 12 to 24 h in every three to four weeks for change of segments. Up to the 1990s, the interval of high-production casters used to be as short as about two weeks. The campaign life of segment rolls was extended significantly because of the improvement in hard-facing technique of roll surfaces, improvement in leakage prevention of bearing cooling water, and continuous oil-mist lubrication of the bearings.

Extending the machine length of a continuous caster means addition of segments, and as a result, the number of roll changes increases naturally. Nevertheless, the number of periodical shutdown was decreased significantly by measures such as improvement in the service life of the rolls and bearings and introduction of quick segment changers such as segment extractors. In addition, precise measurement of roll alignment by advanced roll gap meters made it possible to detect problems of the rolls and bearing at an early stage; this effectively decreased the quality problems of slabs/blooms.

The service life of molds once was 600 to 1,000 charges, shorter than the interval of periodical shutdown, and it was necessary to stop casters for 2 to 3 h for mold change only. Recently, the technology of mold surface coating advanced significantly, and because of plating with Co–Ni alloys, improvement in flame spraying method, and modification of foot rolls, the mold change interval was extended to 2,500 to 3,000 charges; now, mold change is included mostly in periodical shutdown.

4.4 Sequential casting of more charges (increase in casting time)

The number of charges cast through a continuous caster without interruption between insertions of the dummy bar differs from caster to caster depending on factors such as the size of a production lot of the same steel chemistry, service life of submerged entry nozzles, and occurrence of nozzle clogging and other troubles in the teeming system. There used to be cases such as the following: when it was necessary to cast many small lots of different steel grades, they were cast without interruption, allowing for yield loss due to scrapping of joints between two steels where they were mixed; and with some other casters in which the number of charges cast continuously was limited mainly by the service life of submerged entry nozzles, they were quickly changed together with the tundish without stopping the caster.

At present, mass-produced steels are grouped into large lots of 10 to 15 charges (3,000 to 5,000 t) for casting without interruption. This was made possible by improvement of countermeasures against clogging of teeming systems taken at different works. Nagoya Works developed a method whereby submerged entry nozzles were changed during casting without tundish change; this has been put into actual practice.

Small-lot steels are cast continuously by using sequence blocks or inserting steel plates at the joints of different grades to minimize the mixing of steels. Various measures were established to decrease the amount of scrap around the joints, such as optimum casting sequence of steel grades and more flexible utilization of slabs/blooms containing the steel joints; these measures increased the casting yield by 2% to 3% from what it was around 1990.

4.5 Decreasing preparation time between casts

The preparation work between the casts includes extraction of the final piece, insertion of the dummy bar, tundish change, and mold sealing. The final piece of the previous cast is carefully extracted to prevent bleeding, a trouble of molten slag or steel flowing out from the upper end, where solidification is often insufficient. To do this quickly is important to shorten the preparation time; the present field practice represents an optimum method established through many trials and errors.

As for the dummy bar insertion, the downward-inserting type is presently the main stream because the dummy bar can be inserted while the final cast piece is being extracted. In case of using the upward-inserting type, in contrast, dummy bar insertion must wait until the final piece gets out of the caster completely, which increases the preparation time by 10 to 20 min. Thus, most dummy bars of the upward-inserting type were modified into downward-inserting type on the occasions of revamping.

5. Measures for Production of Higher-quality Steels

The requirements of steel users have diversified, and higher functionality is looked for in terms of weight reduction, better workability, higher strength, etc. Stricter control of surface defects and elimination of internal defects came to be demanded. All these, together with the pursuit of higher yield and productivity, have made the quality level required for the steelmaking process increasingly demanding. On the other hand, it is true that such increasingly tougher user requirements brought the technical capability of the Japanese steelmakers to the world's highest level.

Use of steel materials that allow reduction of product weight is one of the latest trends in view of energy and environmental conservation. Lighter weight of car bodies, for example, is good for energy saving and is environmentally friendly because it enhances fuel efficiency and decreases exhaust gas emission. To make this viable, however, the strength and toughness of steel materials must be increased to allow use of thinner sheets, and for steel material to withstand heavy working, it must contain as little inclusion and segregation as possible. In the meantime, heavy steel plates came to be used in increasingly tougher conditions, and accordingly, their thickness increased. This, however, made it difficult to secure sufficiently high reduction ratio (cast slab thickness/product thickness), and consequently, further decease in center segregation and porosity came to be required of steelmaking processes.

The measures taken in the CC process in response to the requests for higher steel quality are explained below.

5.1 Minimizing inclusions

Minimizing inclusions in the mold is one of the most important quality issues of continuous casting. Inclusions deteriorate the mechanical properties of steel under tension, bending, hole expanding, press forming, and other types of working, and cause surface defects. Therefore, it is of great importance to minimize contamination of steel and remove inclusions from it in the CC process. This subsection relates the technologies for preventing inclusions from being entrapped in the surface layers and the center of cast slabs/blooms.

5.1.1 Measures to minimize inclusions in surface layers

Because of conspicuity, the steel sheets for automotive outer panels must be free of surface defects. The typical surface defects originating in steelmaking processes are those due to inclusions of alumina and mold powder. They are caught in initial solidification shells, and when the steel is rolled either in hot or cold, they are stretched and form defects in streaks at the surface; they are called spills, scabs, or slivers. Such inclusions near a surface of slabs can be removed by scarfing, but since scarfing involves costs and decreases yield, it is preferable to minimize their entrapment during the initial solidification in the CC mold. The M-EMS mentioned earlier was introduced for this purpose [5, 6] (**Fig. 5**); it makes steel immediately inside the solidification shells to flow at a prescribed speed or faster to prevent inclusions from being entrapped in the shells.

As for mold powder, to prevent its entrapment, the viscosity of the powder was increased, the control accuracy of the molten steel level in the mold was improved, the mold oscillation was modified, and the influx of molten steel into the mold was rendered more stable. As a result, surface defects due to inclusions originating from the powder decreased markedly.

In addition, to minimize the amount of inclusions getting to the mold, measures were taken to separate inclusions from steel in the tundish as much as possible. One such measure is enlargement of the tundish capacity, commercially practiced at Oita, Hirohata, and other works. A tundish serves as an intermediate holder to ensure stable steel flow from the ladle to the caster mold, and in case of a multistrand caster, distribute steel to the strands. By increasing the tundish size, it is possible to let inclusions float up to the molten steel surface more easily and to suppress the suspension of slag in steel at the teeming position from the ladle. Tundishes of various shapes were developed besides the conventional T-shaped or boat-shaped tundishes. An example is the one vessel divided into two with a tunnel in between, such as the H-shaped tundish of Nagoya Works (**Fig. 6**). Another example is that of Muroran; it is composed of three separate vessels, and the one at the center, which receives steel from the ladle and distributes it to the other two, is equipped with an induction heater.

As mentioned above, heating of steel in the tundish has been introduced to keep the steel temperature within a prescribed range and

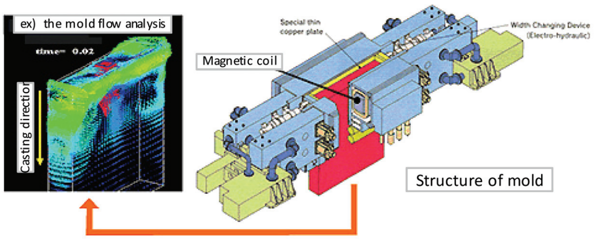

Fig. 5 Schematic of mold structure and example of mold flow analysis

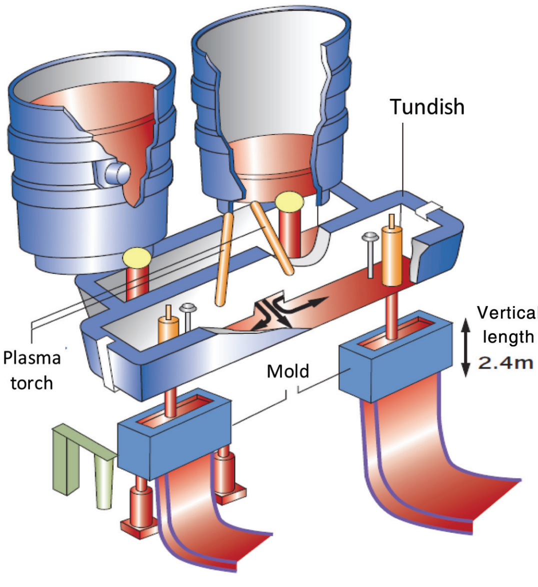

Fig. 6 Configuration of No. 2CC in Nagoya Works

help the floatation of inclusions; either plasma heating or electric induction is used for this purpose.

5.1.2 Measures to minimize internal defects

Tinplates are drawn to a thickness of 0.1 mm or less during can making. There are many similar cases, and such products are subject to strict control of internal defects due to inclusions. In continuous casting, every measure against inclusions must be taken on slabs for these products at the tundish and the mold. The most common countermeasure is revamping the caster from the curved-mold type into the VB type; making cast steel follow a vertical line of 2 - 3 m from the mold is effective at letting inclusions float up to the molten steel surface and be removed from the cast.

Additionally, it is necessary to control the downward flow of steel in the mold so that inclusions are not carried by it and caught in the steel. To this end, level magnetic field electromagnetic brakes (EMBs) have been introduced to some casters. When a static magnetic field is applied to the inside of a mold, a force in the opposite direction of the steel flow arises, which is used for decelerating the downward flow to facilitate the floatation of the inclusions. Some curved-mold casters not having EMBs are equipped with strand-electromagnetic stirrers [7, 8] to make steel flow upward and prevent inclusions from going down and being caught in the cast.

5.1.3 Oxide metallurgy

Nippon Steel Corporation developed oxide metallurgy,[9, 10] whereby nonmetallic inclusions that cause defects are removed, and at the same time, deoxidizing conditions are controlled such that oxides are dispersed in fine particles of steel to enhance material properties. This technology makes use of fine oxide particles as the nucleation sites for precipitates and the γ/α transformation. It is effective, for example, at improving the toughness of the heat-affected zones of weld joints of heavy plates, and in appreciation of this, it is widely applied to marine structures and the like. Recently, steel for high-heat-input welding applications, called H-TUFF steel, was developed by applying oxide metallurgy, wherein oxide particles, some tens of nanometers in size, dispersed in steel are used for hindering crystal grain growth. Thus, oxide metallurgy is proving effective at greatly enhancing the added values of steel products.

5.2 Measures to minimize center segregation

As mentioned before, the use conditions of steel materials are becoming increasingly demanding; this is true especially with heavy plates for marine structures, line pipes, and sheets for automotive structures that undergo hole expanding work. In this situation, to satisfy the properties required of steel materials, such as better workability, higher strength, less weight, and lower reduction ratios, it is important especially to minimize center segregation and porosity. Decreasing center segregation is also important with bars and wire rods since it helps improve cold working properties and simplifies, or even eliminates, homogenization and diffusion treatment.

To improve segregation by applying light reduction to cast slabs/blooms at the solidification completion position near the exits of continuous casters, Nippon Steel Corporation developed and commercially employed the “CC optimum reduction by divided rolls (CORD)” method using solid, divided rolls, and the segregation-free technology (SEFT) using pressing rams.[11] On the basis of the knowledge and experience of these methods, the company incorporated the most advanced countermeasures against center segregation in No. 6 CC of Kimitsu Works for mass-producing products sensitive to center segregation. The same technology is also commercially applied to the bloom casters of Muroran, Kimitsu, and Yawata Works.

6. Technologies Supporting High-speed Casting of High-quality Steels

Since steelmaking processes deal with molten metal at high temperatures, it is not easy to accurately follow the molten steel behavior, for example, the surface properties of hot slabs/blooms in detail during the CC process. However, to improve the quality of slabs/blooms and increase casting speed, it is necessary to accurately understand the bulk flow, the inclusion behavior in molten steel, and the nature of cast pieces, which cannot be seen directly, and reflect them in the field actions of quality improvement and operation stabilization. To this end, Nippon Steel Corporation has improved technology for directly measuring actual phenomena, as well as for analyzing them, using model calculation.

6.1 Analysis technology

CC is a complicated process dealing with the behavior of microscopic inclusions in a mixed flow of molten steel, slag, and gas, and therefore, it is not easy to monitor and control all that occurs in the process that stretches across tens of meters. Recently, however, because of advances in simulation models, it has become possible to understand various mutually correlated process phenomena.[5]

For example, optimum tundish shape was defined through analysis of the difference in the behavior of inclusions of different sizes in tundishes of different shapes using coupled models that could handle gas and liquid.

As mentioned in 4.2.2, Nippon Steel Corporation has improved the shape of mold copper plates and defined the optimum casting speeds for different steel temperatures using solidification simulation models. Furthermore, operation conditions ideal for preventing gas bubbles and inclusions from being caught in the solidification shells were defined, using coupled models for molten steel and gas bubbles in the mold, and such ideal operation conditions have actually been applied to daily practice.

In addition, the formation mechanism of center segregation was made clearer by simulation models of the cast bulging between segment rolls and the formation of center segregation due to steel flow at the dendrite tips at the final solidification stage, and it became possible to quantitatively predict how different factors would influence the formation of center segregation. These findings were reflected in the design guidelines for equipment and operation, and center segregation decreased significantly.

More recently, attention was paid to the behavior of secondary cooling water to cool casts in the segments, and calculation models made it clear that falling water got together between the bearings, where the segment rolls were divided, over-cooled the cast steel, and caused uneven cooling in the width direction.[12]

Nippon Steel Corporation has effectively applied the thermodynamic equilibrium calculation program, SOLGASMIX, to the prediction of the composition of deoxidation products, oxide metallurgy, etc.[13]

6.2 Measurement technology

Since CC is a process for solidifying molten steel, temperature measurement is of basic importance. Continuous temperature monitoring in tundishes, a common practice nowadays, is indispensable for stable caster operation and quality assurance. To continuously monitor the lateral temperature homogeneity of cast steel, surface temperature is measured between segments using radiation thermometers. For quality assurance of slabs/blooms, defect detectors are provided at transfer tables at the exits from casters; they effectively prevent defective slabs/blooms from going downstream by spotting small defects in hot, which is difficult for human eyes.

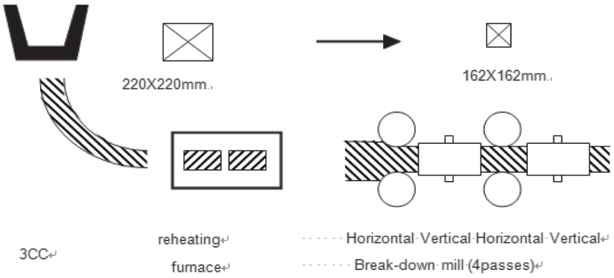

Fig. 7 Schematic illustration of NCR process

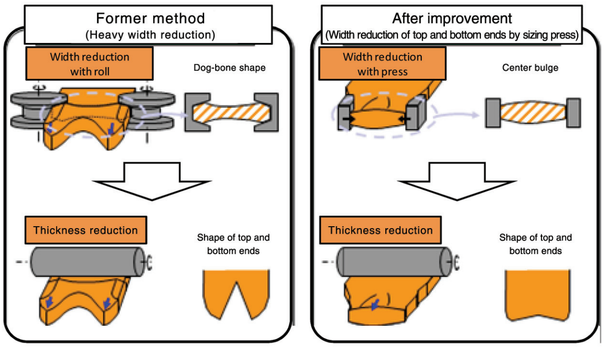

Fig. 8 Introduction of sizing press at Oita Works

7. High-efficiency Production through Combination of Continuous Casting and Breakdown Rolling

7.1 Direct link of continuous casting to breakdown rolling at Muroran Works

Muroran Works used to cast 350 × 560 mm^2 large-section blooms for bar products and 162 × 162 mm^2 small-section billets for wire-rod products. To enhance production efficiency, this was replaced in 1998 by a new process called the “near-net-shape casting and compact high reduction (NCR)” process directly linking a bloom caster with a compact breakdown mill.[14, 15]

By the new process, the small-section billets, which had been either cast through a billet caster or cast through a bloom caster and then rolled through a breakdown mill, came to be cast through the bloom caster in a section size of 220 × 220 mm^2, charged into a reheating furnace close to the delivery end of the caster while hot, and after the reheating, rolled into small-section billets through the breakdown mill capable of applying heavy reduction, effective at material improvement (**Fig. 7**).

The NCR process having the advantage of homogeneous and isotropic material properties, characteristic of square, medium-section molds, has reduced the costs of breakdown rolling through process simplification, and dissolved the problems of limited reduction ratio and low productivity due to the former small-section casting.

7.2 Addition of sizing press to “Direct Link Process V” of Oita Works

Under a system called the “Direct Link Process V,” consisting of large-section casters and a closely coupled sizing mill, the continuous casters of Oita Works produced slabs of fixed sizes with minimum number of size changes. While this method was suitable for mass production and made the most of the production capacities of the casters, the slab ends turned into long fishtails at the sizing rolling and were scrapped down, which caused considerable yield loss. As a solution, a sizing press was installed in 2009 between the reheating furnace and the mill to reduce the slab width at the top and bottom ends before the sizing rolling (**Fig. 8**). This decreased the fishtail length, and as a result, the integrated yield improved significantly.[16]

8. Slab/Bloom Conditioning

Slabs and blooms coming from continuous casters undergo surface conditioning, which is carried out mainly by combining machine scarfing of all surfaces and partial scarfing. Significant advance has been made in this field over the last years. Machine scarfing of hot slabs/blooms combined with grinding in hot has greatly increased the hot conditioning capacity, improved surface quality, and increased the ratio of hot charge rolling. Although surface conditioning of slabs/blooms is important for good surface quality of final products, it decreases the yield. An important future task of CC in consideration of this is to enhance the process capacity to incorporate desired quality in slabs/blooms so as to improve the surface quality of IF and crack-sensitive, high-end steels and allow elimination of surface conditioning.

9. Measures to Minimize Excess Materials

The production orders for continuous casters are composed on the basis of purchase orders from customers. If the cast slabs/blooms fail to meet required size and quality, they become excess materials not allotted to any specific customer order. Once marked as excess material, the slab or bloom is left to cool. Excess materials thus occupy plant areas disturbing the process flow of the works, and when it is allotted to an order, it will have to be heated again, which means increased costs. Nippon Steel Corporation has bent efforts to minimize the occurrence of excess materials and accelerate their allocation to salable products. Aiming especially at minimizing their occurrence, besides technical improvement to avoid inadequate product quality, the company established and commercially applied a system to allocate steel being cast to suitable purchase orders in hand.

10. Closing

The CC technology for high-speed casting of high-quality steels and efficiency enhancement has been outlined herein. As stated earlier, the Japanese steel industry is facing stagnant domestic demand and competition from developing economies, and to strengthen its position in the world market in such a situation, the industry must further enhance its technology that it has fostered and accumulated.

As described in other articles of the present issue, Nippon Steel Corporation has developed wide varieties of CC technologies for high-speed casting of high-quality steels. In addition, helped by the advances in analysis technology, causes of problems have been made clearer and clues to their solution found, and as a result, it is now possible to take effective measures to minimize the occurrence of inclusions and remove them. Thus, we have come closer to producing defect-free slabs/blooms, free of center segregation or cracks that form during solidification, and will continue to challenge this target.

It is often said that the strength of the Japanese steel industry lies in its technical capability and the people on the work floor. In the CC process, which still depends much on human labor, operators’ skill and technology that support it form synergistically the foundation for stable production of high-quality products. In the present situation where we face tough competition in a global market, enhancing our technical capability and the power of the people on the work floor is the only way to make our future brighter.

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