

# Development of Steelmaking Processes for Producing Various High-Quality Steel Grades at Yawata Works

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## Abstract

*In the early 1980s, when all of the ironmaking and steelmaking plants at Yawata Works were transferred from the Yawata area to the Tobata area, three steelmaking plants had been producing various type of steel grades, such as sheets, electrical steels, rails, shapes, pipes and stainless steels. After that, it became necessary to meet the growing demand for producing high-grade steel and to restructure the production process by reducing the number of blast furnaces. Therefore, new technologies have been actively developed and introduced to drastically improve the productivity and the steelmaking technologies. These measures enabled us to streamline the production facilities and to establish a highly-efficient steelmaking process which can offer a wide variety of high-grade steel.*

## 1. Introduction

There are many technologies that support today's steel industry. Of these, the most important are the converter, which has put an end to the open-hearth furnace; the vacuum degassing process, which is used for the secondary refining of molten steel; and continuous casting (CC), which has completely replaced ingot casting. In Japan, those technologies were introduced in the 1960s when crude steel output increased markedly. During this period, more and more converters having larger capacities were effectively employed. The first and second oil crises and the rising yen in the 1970s accelerated the adoption of continuous casters that offered high yield, high productivity, and superior energy efficiency. Under these conditions, in 1979, Nippon Steel Corporation's Yawata Works moved all its main steelmaking plants to the Tobata area and shut down its small-scale steelmaking plants in the Yawata area.

Subsequent to the move to Tobata, the number of blast furnaces in operation was reduced to a single furnace, calling for a drastic revision of the constitution of the steelmaking processes of Yawata Works. As a simultaneous development, customers were demanding steel products of increasingly sophisticated properties and it became urgently necessary to develop new technology for manufacturing high-grade steels (high-purity, high-cleanliness steels). In particular, Yawata Works that was manufacturing a wide variety of steel prod-

ucts was required not only to integrate the steelmaking plants, shut down the blooming/slabbing mills, and coordinate the continuous casters but also to establish efficient production processes through the development and introduction of advanced new production technologies (Fig. 1).

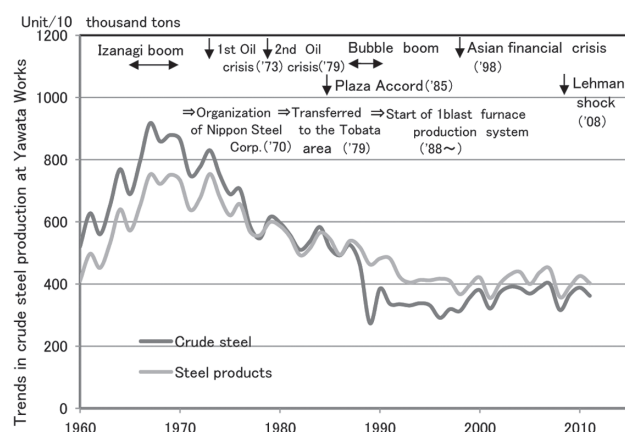


Fig. 1 Trends in crude steel production at Yawata Works

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In this report, we shall first briefly review the history of the steelmaking plants of Yawata Works for the past 30 years, from the early 1980s to the present, and then describe the Works' technologies for manufacturing a wide variety of steel products.

**2. History of Steelmaking Plants of Yawata Works**

In 1969, Yawata Works formulated a master plan<sup>1)</sup> to strengthen its manufacturing organization that was at that time inferior to that of the, then-modern, Sakai Works and Kimitsu Works. The stated goals of the master plan were nearly accomplished by the early 1980s. Looking at the development of Yawata's steelmaking processes, the No. 3 steelmaking plant—a large-scale plant—was constructed in the Tobata area.<sup>2)</sup> The construction of this plant completed the planned integration of the ironmaking and steelmaking departments in the Tobata area. As a result, Yawata Works came to have three steelmaking plants—the No. 1 steelmaking plant (C plant), the No. 2 steelmaking plant (N plant), and the No. 3 steelmaking plant (T plant), which were manufacturing a wide variety of steel products. Each of the steelmaking plants had refining processes using a converter and ingot casting and CC processes. For some time, the C plant was producing blooms for rails, shapes, and seamless pipes; the N plant was manufacturing slabs for sheets, plates, electrical steel, and stainless steel sheets; and the T plant, owing to its large converter, was producing slabs for sheets and blooms for shape and pipe steel, which offered economies of scale.

Subsequently, as steel output continued to level-off, Yawata Works further reorganized its production facilities to concentrate on specific steel grades to improve productivity and to meet customers' stringent quality requirements. Today, the T plant plays a leading role in the manufacture of steel products at Yawata Works. The change in Yawata Works' steelmaking processes in the past three decades is illustrated in Fig. 2, and the development of its product mix, from 1982 to 2011, is shown in Fig. 3.

In the section that follows, we shall describe the development of the refining, slabbing, and CC processes and manufacturing technologies that have made it possible to reliably produce a wide variety of steel products.

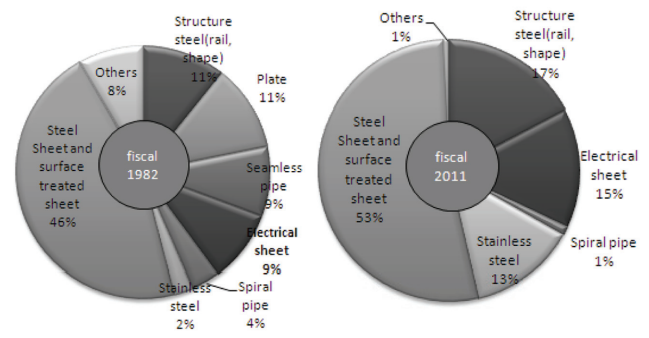


Fig. 3 Changes in product mix

**3. Manufacturing Technology by Process**

**3.1 Integration and functional specialization of refining processes<sup>1,3)</sup>**

Soon after completion of the three steelmaking plants in the Tobata area—the C plant, N plant, and T plant—which were among the most modern and efficient plants at that time, Yawata Works initiated integration of the refining processes of the C plant with those of the N plant<sup>4)</sup> and transferred the ordinary steel refining process of the N plant to the T plant since the number of blast furnaces in operation had been reduced to one. As a result, the ordinary steel refining process was integrated and specialized at the T plant and the stainless steel refining process was integrated and specialized at the N plant.

We shall describe below the progress of ordinary steel refining technology enacted at the T plant and the progress of stainless steel refining technology exhibited at the N plant.

**(1) Ordinary steel refining technology**

Characteristically, the manufacturing of ordinary steel involves production of many different types of steel for sheets, electrical steel, rails, shapes, pipes, and other components. Namely, a wide variety of steels, from ultra-low-carbon steel to high-carbon steel, are refined by the same refining processes and the supply of refined molten steel is coordinated with the CC process. As indicated by the progress of ordinary steel refining technology illustrated in Fig. 4, the functions of the individual refining processes have continually been optimized to meet customer specifications for specific ordinary steels.

In the hot metal pretreatment process, torpedo car desulfurization (TDS) was put into practical use in 1983 to optimize the desulfurizing function, which made it possible to start mass production of low-sulfur, high-purity steel.<sup>5)</sup> In 1986, oxygen gas was put into practical use to widen the thermal tolerance in the converter.<sup>6)</sup>

Yawata Works also developed techniques to predict and restrain “slopping,” a phenomenon that becomes a problem during dephosphorization treatment by TDS, and established a technique for stable

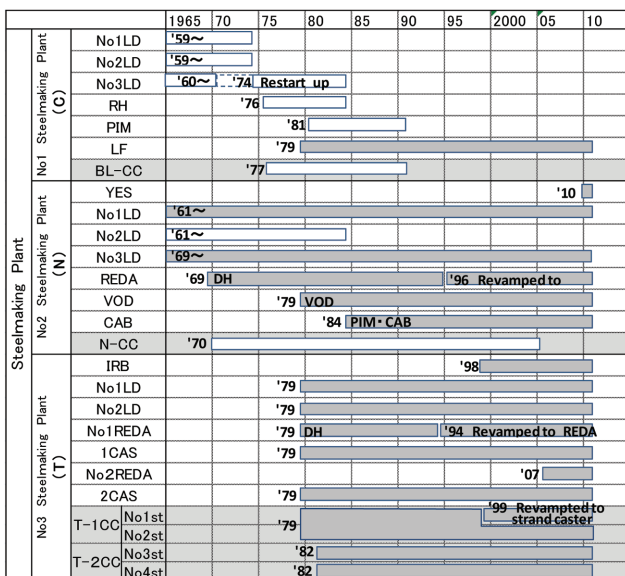


Fig. 2 Changes in the steelmaking process at Yawata Works

A.D.	Hot metal pretreatment	Primary refining	Secondary refining
	deSi, deS, deP	deC·deP	Ultra-low-carbon processing Degassing, Deoxidation
~ 1983	deSi·deC·deP (LD-OB))		DH-CAS
1983~	deSi, deS, deP in TPC (TDS)	deC·deP (LD-OB)	DH-CAS
1995~	deSi, deS, deP in TPC (TDS)	des in ladle (Inj.)	REDA-CAS
1994~	deS in ladle (KR/Mg-inj.)	MURC/deC·deP (LD-OB)	REDA-CAS

Fig. 4 Transition of ordinary steel refining technology at Yawata Works

dephosphorization treatment using a torpedo car.<sup>7, 8)</sup> Thereafter, magnesium desulfurization equipment for obtaining ultra-low-sulfur steel was installed in 1995.<sup>9)</sup> In addition, in response to the demand for defluorination of slag, reflecting the environmental regulations that have become increasingly stringent, the Works replaced the conventional desiliconization and dephosphorization processes with a pretreatment process using a converter<sup>10)</sup> and installed new desulfurization equipment provided with a mechanical stirrer (KR: Kanbara Reactor) having excellent desulfurization efficiency.<sup>11)</sup>

For the primary refining process, various R&D projects relating to the refinement of hot metal using a large, top and bottom-blowing converter were carried out prior to the construction of the T plant.<sup>12-17)</sup> Several top and bottom-blowing converters were developed and tested during the period 1977-1979. In 1980, one year after start-up of the T plant, a 350-ton converter was put into operation as Japan's first LD-OB (LD-oxygen bottom blowing) process.<sup>18)</sup> Two months later, a 170-ton converter of the same type was also put into operation at the N plant, paving the way for the application of LD-OB in the refining of stainless steels to be described later. Thereafter, the Works established LD-OB refining technology that utilized a large-capacity converter, which helped to improve the metallurgical properties of steel through reduction of the loss of such metallic elements as iron and manganese in oxidation and through the restraint of slopping,<sup>19-23)</sup> and which, later, led to the introduction of technology for reducing manganese ore.<sup>24, 25)</sup> In the field of operations too, the Works introduced a automatic blowing system accomplished mainly by dynamic control using a sub-lance and an OG (oxygen converter recovery process gas) automatic operation system, thereby establishing a fully automatic blowing operation.<sup>26)</sup> After the number of blast furnaces was reduced to only one in 1989, the Super Ultra Low HMR Operation (SULHO) was established to maximize the output of crude steel from a limited amount of hot metal.<sup>27, 28)</sup>

For some time, a smooth material flow from the blast furnace to the steelmaking plant was impeded because of an imbalance between the plant's hot metal tapping capacity and molten steel tapping capacity, whereby even the CC process were adversely affected. Owing to this condition, a world-class iron reserve barrel (IRB) with induction heaters, shown in Fig. 5, was put into operation in 1998.<sup>29)</sup> As a result, it became possible to provide an uninterrupted supply of molten steel to the four continuous casters that cast steel grades requiring different production speeds on a sequential casting basis. In addition, the hot metal buffering function of the IRB has made it possible to decrease by half the number of torpedo cars in operation carrying hot metal from the blast furnace to the steelmaking plant. Furthermore, whenever the blast furnace is functioning at a substandard level or the demand for tapping of steel increases sharply, it is possible to produce quasi-hot metal by utilizing the

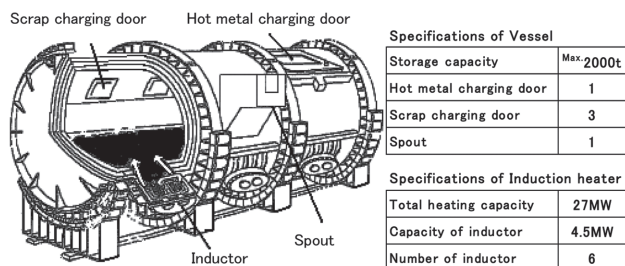


Fig. 5 Iron reserve barrel with induction heater

IRB to melt cold pig iron and scrap iron. Thus, by selecting the optimum principal raw materials according to a specific steel grade, Yawata Works is manufacturing high-grade steel products efficiently.

For the secondary refining process, the Works developed a simple ladle refining process called CAS (composition adjustment by sealed argon bubbling) to improve the alloy yield, composition hit rate, and steel cleanliness.<sup>30)</sup> The CAS process was introduced into the N plant in 1977 and into the T plant in 1979, and facilitated production of steel grades demanding severe composition control. Eventually, the CAS process evolved into the CAS-OB process<sup>31-33)</sup> and CAS-Inj. process,<sup>34)</sup> each being a simple facility that allowed for temperature adjustment and even the reduction of the converter end-point temperature, as well as for the desulfurization of molten steel. As a simultaneous development, Yawata Works, which had previously, as a means of differentiating its steel qualities from those of newly emerging steelmaking countries, introduced DH equipment for the first time in Japan as a vacuum process for refining ultrahigh-purity steel, developed and introduced an improved version of DH to implement speedy, mass refinement of steel as the T plant was put into operation in 1979.<sup>35)</sup> Five years later, in 1984, the DH equipment of the N plant was also upgraded to an improved version.<sup>36, 37)</sup> As a result, the refining levels of carbon, nitrogen, and hydrogen were improved markedly. Also, with respect to deoxidation of steel, this newly developed DH equipment made it possible to treat a large quantity of steel relatively easily.

Subsequently, in order to further advance the technological development aimed at improving the RH degassing performance rapidly, the Works developed a degassing process with single large immersion snorkel and a bottom bubbling ladle, called the revolutionary degassing activator (REDA) based on the DH equipment shown in Fig. 6.<sup>38-41)</sup>

The vacuum refining equipment of Yawata Works requires technology that permits manufacturing a wide variety of steel grades, ranging from ultra-low-carbon steels ( $[C] \leq 10\text{ppm}$ ) to high-carbon steels ( $[C] \geq 1\%$ ). The REDA that does not use a vacuum tank and is capable of reducing the contamination of the steel being treated by the pretreated charge allows for continuous processing of both ultra-low-carbon steel and high-carbon steel. Thus, it can be said that the REDA is a degassing facility suitable for producing a wide variety of steel grades. At present, the Works employs two REDAs to meet the growing need for vacuum refining.

(2) Stainless steel refining technology

The stainless steel manufacturing process at Yawata Works has undergone a series of changes, from the electric furnace vacuum ox-

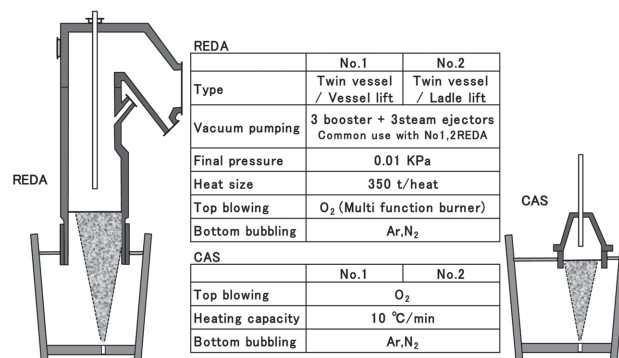


Fig. 6 Secondary steel refining facilities in No.3 steelmaking plant<sup>32, 41)</sup>

ygen decarburization (EF-VOD) process to the EF-LD-VOD process (in the Yawata area) and then to the BF-LD-VOD process in the N plant in 1979 and finally to the present BF/EF-LD-REDA/VOD process. In the meantime, amid the company-wide movement to integrate ironmaking and steelmaking sources, the production of stainless steels at Yawata Works has increased markedly through the transfer of stainless steel manufacturing operations from Muroran Works to Yawata Works and the mutual stainless steel supply system established with Sumitomo Metal Industries, Ltd. and Nisshin Steel Co., Ltd. Today the Works supplies ferritic stainless steels to Nippon Steel & Sumikin Stainless Steel Corporation. The development of stainless steel refining technology at Yawata Works is illustrated in Fig. 7.

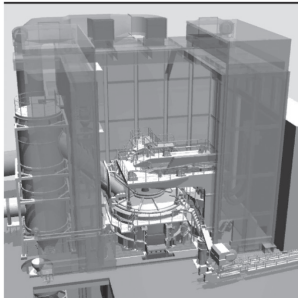
The stainless steel grades that are manufactured at Yawata Works are ferritic and martensitic stainless steels, the majority of which are ultra-low-carbon, low-nitrogen steels called high-purity ferritic stainless steels. In order to offer high-quality stainless steels, the Works has continually revolutionized the manufacturing process with an emphasis on establishing technologies for pretreatment and purification of blast furnace hot metal that has the benefit of cost competitiveness.

For the pretreatment of hot metal, the Works developed the so-called soda injection dephosphorization (SIDP) process whereby the hot metal is desiliconized and dephosphorized by soda injection in the ladle. The SIDP process was developed into commercial production equipment first for the manufacture of stainless steels, rather than ordinary steels.<sup>42)</sup> Eventually, however, it was replaced with a TDS-based hot metal dephosphorization process since SIDP was found to have several problems, such as the need to treat sodium-containing slag and the susceptibility of equipment to corrosion.

Concerning the primary refining of stainless steel, a new refining process using a top and bottom-blowing converter was developed at the N plant, which led to the establishment of a more efficient stainless steel manufacturing technology.<sup>43-47)</sup> The principle factor in the manufacturing of stainless steel is selection of the optimum principal raw materials, including the selection of chromium, which largely determines the manufacturing cost. Therefore, at one time, the Works developed a chromium ore melting and reduction process for reducing the consumption of ferrochromium alloy.<sup>48-53)</sup> However, in view of the cost and environmental impact of the process, the Works chose not to proceed with developing it commercially. Instead, the Works focused on developing a highly efficient refining operation in which ferrochromium alloy was continuously input into the converter from the top. At the same time, with the aim of increasing overseas procurement of ferrochromium alloy and recycling chromium-containing scraps, the Works introduced a ferroalloy melting process

A.D.	Hot metal pretreatment	Primary refining	Secondary refining
	deSi,deS,deP	deC·Cr-addition	Ultra-low-carbon processing Degassing, Deoxidation
~1980	deSi,deP (LD)	deC·Cr-addition (LD-OB)	VOD
1980~	deSi,deS,deP in ladle (SIDP)	deC·Cr-addition (LD-OB)	VOD
1983~	deSi,deS,deP in TPC (TDS)	deC·Cr-addition (LD-OB)	VOD-CAB
1995~	deSi,deS,deP in TPC (TDS)	deC·Cr-addition (LD-OB)	REDA/VOD-CAB
1994~	deSi,deS,deP in TPC (TDS)	deC·Cr-addition (YES+LD-OB)	REDA/VOD-CAB

Fig. 7 Transition of stainless steel refining technology at Yawata Works



Main specifications of furnace	
Type	Three-phase AC
	Replace furnace body
Heat size	90 t/ch
Stirring	Bottom blowing gas stirring
Capacity of Transformer	90 MVA
Electrode size	24 inch
Type of Tapping	Gutter pouring
Auxiliary burner	O2-COG burner

Fig. 8 Iron alloy melting furnace

called the Yawata environment-friendly smelter (YES),<sup>54)</sup> thereby establishing an environmentally-friendly material circulation system (Fig. 8).<sup>55)</sup>

For the secondary refining of stainless steel, the principle factor is enhancing the efficiency of oxygen blowing under a reduced pressure (low CO pressure) that is characteristic of the refining of stainless steel. Therefore, after introduction of VOD equipment into the N plant,<sup>56)</sup> the Works adopted a water cooling system for the oxygen blowing lances, optimized the distribution of the decarbonization load between the converter and the refining process through the application of high-speed decarbonization technology,<sup>57)</sup> modified the VOD equipment into a pit form,<sup>58)</sup> and divided the finish refining function of CAB (capped argon bubbling). In addition, the Works introduced REDA equipment having a high-efficiency vacuum decarburization characteristic and secured a greater upward elasticity of stainless steel production capacity by implementing the simultaneous operation of VOD and REDA. Furthermore, concurrently with the innovation in its manufacturing processes, the Works pressed ahead with the improvement of refractory materials and repair techniques and the establishment of waste recycling technology.

As has been described above, Yawata Works has established an ordinary steel refining process for efficiently refining a wide variety of ordinary steels for automotive sheet (interstitial free (IF) steel sheet), tinplates, electrical sheets, high-carbon steel sheets, rails, shapes, and other purposes. Additionally, the Works has established a stainless steel refining process for refining ferritic and martensitic stainless steels, the majority of which are ultra-low-carbon, low-nitrogen steels called high-purity ferritic stainless steels.

### 3.2 End of the blooming/slabbing processes

The beginning of the end of the blooming/slabbing processes at Yawata Works dates back in the 1970s. In those days, following the transfer of the ironmaking and steelmaking departments of the Works from the Yawata area to the Tobata area, the Works' first continuous slab caster (N-CC put into operation in 1970) and continuous bloom caster (C-BL-CC put into operation in 1977) started commercial production, and gradually replaced the obsolete blooming and slabbing mills in the Yawata area. The five blooming/slabbing mills (3 in the Yawata area and 2 in the Tobata area) that were operating in 1975 were consolidated into three mills in 1980. And, by 1984, two of the remaining three mills, the No. 6 slabbing mill of Yawata and the No. 2 slabbing mill of Tobata, were also shut down because of their obsolescence, poor energy efficiency, and other reasons, leaving only the No. 1 mill of Tobata in operation. In this subsection, we shall review how the blooming/slabbing process was brought to an end and describe the steel production facilities and manufacturing methods that have been left behind by the blooming/slabbing technology (Fig. 9).

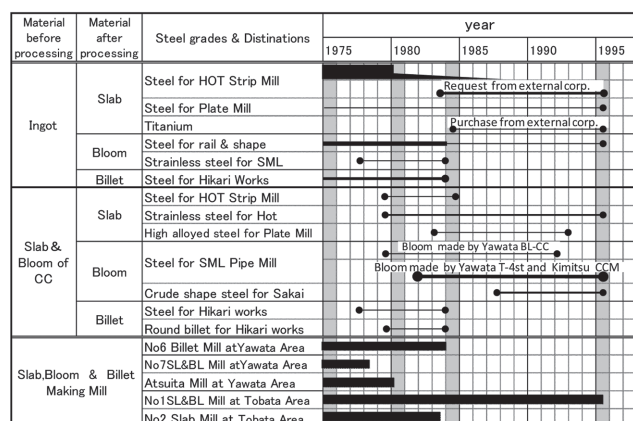


Fig. 9 Changes in types of semi-finished casting products for primary rolling

(1) Ingot rolling technology

The blooming/slabbing process gradually disappeared as more and more ingots came to be cast continuously, and the commissioned rolling of ordinary steel ingots was eventually switched to the commissioned casting on the No. 1 CC of the T plant. Therefore, facilities for transporting molten steel from the N plant to the T plant were established beforehand.

Prior to the disappearance of ingot rolling, it was questioned if the time saved by elimination of the ingot rolling process could be used to improve the yield in the blooming/slabbing process. That idea led to the development of special rolling processes, such as the one-way rolling process and the double one-way rolling process, thereby enhancing the blooming/slabbing yield dramatically. In particular, the yield in slabbing of capped steel improved as much as about 3%.<sup>1)</sup> Even so, the conventional blooming/slabbing process could not check the strong current of growth in CC

(2) CC-slabbing process (CC breakdown)

The No. 1 mill of Tobata, which was originally constructed as a slabbing mill, was eventually transformed into a blooming and slabbing mill for rolling various types of steel products of varying shape in response to the rationalization of blooming/slabbing operations.

Specifically, when a small-diameter seamless pipe plant was started in April 1983, large-section blooms (320 mm × 450 mm) cast by the No. 4 strand of the T plant were downsized to smaller-section blooms (220 mm square/290 mm square) (CC breakdown). In addition, in order to increase the production capacity to 40,000 tons/month, a recuperator was constructed in January 1984<sup>3)</sup> to cope with the increase in the amount of CC breakdown steel in the slabbing process and to improve the productivity of the continuous caster.

After that, as a result of the casting of small-section blooms by a continuous caster (representing the establishment of as-cast technology) and the application of HCR (hot charge rolling) to ferritic stainless steel for hot rolling, the blooming/slabbing process of Yawata Works disappeared completely. And, since the breakdown rolling of large shaped blooms (VIII B Type) and deformed blooms (Z type) for Sakai Works and the breakdown rolling of hot protruding round bars and the rolling of titanium sheets for Hikari Works were transferred to other steelworks, the No. 1 slabbing mill of Tobata was shut down in July 1995, putting an end to the blooming/slabbing mills of Yawata Works. The molten steel transportation line built between the N plant and the T plant and the HCR process established in the course mentioned above paved the way for the eventual integration of the refining and CC processes.

3.3 Functional differentiation of the CC process and the integration of production

At the same time that the T plant was constructed in 1979, the 1-ladle, 2-strand continuous slab caster (T-1CC) was put into operation.<sup>59, 60)</sup> Three years later, in 1982, two 1-ladle continuous slab/bloom casters—T-2CC No. 3 and No. 4 strands—were put into operation as well.<sup>61)</sup> After that, the T-1CC was subject to several modifications, such as the separation of strands and the adoption of vertical bending. Employing the four single-strand continuous casters—the No. 1 strand to the No. 4 strand, each having unique characteristics (Table 1), Yawata Works presently manufactures a wide variety of steels, ranging from slabs for high-grade tinplates, automotive sheets, electrical sheets, stainless steel sheets, and high-carbon steel sheets, to billets for rails, shapes, and sheet piles. Thus, the Works has strengthened its competitiveness by manufacturing specific steel products, while employing the specific continuous caster strand that provides for optimum productivity, quality, and cost. In this subsec-

Table 1 Main specifications of continuous casters

	No.1 strand	No.2 strand	No.3 strand	No.4 strand
Type	Slab (single) Bloom (triple) Curved	Slab (single) VB	Slab (single) VB	Slab (single, twin) Bloom (triple) Curved
Strand	1	1	1	1
Heat size (ton)	160, 350	350	350	350
Casting size (mm)	250 × 650-1650 290 × 1900 □ 220, □ 290	250 × 650-1900	250 × 960-1650	250 × 960-1800 200 × 480, 640 320 × 380
Bending radius (m)	10.5	7.55	7.73	10.5
Vertical length (m)	—	2.5	2.5	—
Machine length (m)	30.7	38.7	31.7	30.4
Tundish capacity (ton)	30	30	23	23
Tundish heater	Plasma heater	—	Induction heater	Induction heater
EMS	M-EMS S-EMS	M-EMS S-EMS	M-EMS	S-EMS

tion, we shall describe the progress of the Works' casting technology with a focus on 1) special steel casting technology, 2) ordinary steel casting technology, and 3) bloom casting technology.

(1) Special steel casting technology (No. 1 strand)

The No. 1 strand is a continuous caster for casting special steels, including slabs of stainless steel and high-carbon steel, and blooms of 13%Cr steel for seamless pipe. This continuous caster was formerly one of the two strands of the T-ICC. Modified into a continuous caster for slab and bloom, the strand was installed at a place about 40 m away from the position of the T-ICC. In the past, stainless steels and high-carbon steels had been cast at extremely low speeds on a Soviet-type, 2-strand vertical continuous slab caster (N-CC) installed in the N plant for forming an equiaxed microstructure and preventing internal cracks and nonmetallic inclusions. However, the introduction of casting and equipment technologies appropriate to specific steel grades has made it possible to cast stainless steels and high-carbon steels on the No. 1 strand. As a result, the productivity has improved dramatically. The casting and equipment technologies that are incorporated into the No. 1 strand are illustrated in Fig. 10.<sup>62)</sup>

One of these integrated equipment technologies is the ladle turret that is capable of mounting two molten-steel ladles with different capacities (350 tons and 160 tons). The 160 ton capacity ladle is used to supply molten stainless steel, and the 350 ton capacity ladle is used to supply molten ordinary steel. In addition, in order to allow for single slab casting and triplet bloom casting, the tundish shape was re-designed, the spray nozzles were rearranged, upper and lower dummy bar insertion devices were newly installed, and so on. The other integrated technologies include an electromagnetic stirrer installed in the mold and strand for efficient casting of stainless steel and high-carbon steel; a small-diameter split roll to shorten the roll pitch as a measure to prevent internal cracking; and a TD plasma heater that permits for a long, continuous casting operation.<sup>63)</sup>

In addition to the abovementioned technologies, Yawata Works established as-cast technology based on the soft reduction technology established for the No. 4 strand continuous caster. The as-cast technology has significantly reduced macrosegregation and center porosity in small-section (220 mm sq.) 13%Cr blooms for seamless pipes, thereby making it possible to omit the breakdown slabbing process.<sup>64)</sup> Incidentally, the production of 13%Cr steel for seamless pipes at Yawata Works was discontinued in 2001.

Because the continuous casting of stainless steels and high-carbon steels, which had been implemented exclusively on the vertical-type N-CC, was transferred to the No. 1 strand, the N-CC was shut down in March 2006.

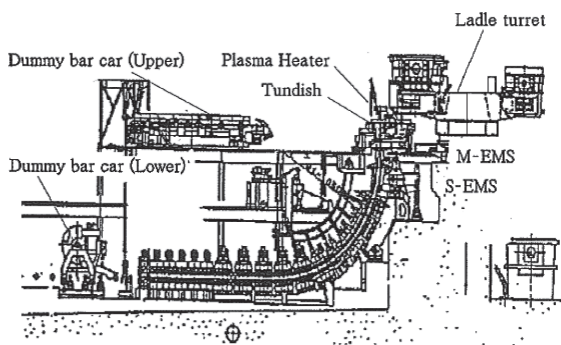


Fig. 10 Key technologies in No.1 strand caster

(2) Ordinary steel casting technology (No. 2 strand/No. 3 strand)

The No. 2 strand is linked to the present hot rolling mill (put into operation in 1982) by a roller table to allow for the HCR operation in which hot slabs put out from the continuous caster are charged into the reheating furnace. Around 1982, the HCR production of low-carbon Al-killed steel and electrical steel was started at Yawata Works. After that, the Works introduced a remote DR (direct rolling) facility linking the hot rolling mill to the T-ICC via high-speed slab carrier cars, and this modification led to the development of a process for hot direct rolling of slabs.<sup>65)</sup>

Electrical steels, especially 3%Si steel, have a wider region of solid-liquid coexistence than ordinary steels and, hence, they are susceptible to internal cracking. In order to prevent internal cracks, therefore, efforts were made to optimize the secondary cooling pattern. As a result, the Works established a technique to cast electrical steels at a high speed of 1.5 m/min to 1.7 m/min.<sup>66)</sup>

In addition, as measures to improve productivity and minimize the occurrence of defects for the high-speed casting operation, the Works has established a number of new technologies including breakout (BO) prediction technology utilizing a neurocomputer;<sup>67)</sup> bath level control technology having an auto-tuning capability;<sup>68)</sup> and labor-saving technology based upon an expert system to permit a continuous caster to be operated by only four persons.<sup>66, 69)</sup> On the basis of the above technologies for improving the productivity and dependability of CC operations, the Works rebuilt the No. 2 strand into a vertically bending type continuous caster in 2005, having a vertical section length of 2.5 m and an electromagnetic stirrer in the mold in order to enhance the flexibility with which it meets quality requirements. As a result, the No. 2 strand has become a single-strand continuous slab caster capable of casting not only middle-grade steels and high-grade steels for tinplates and automotive sheets but also special steels, such as electrical steel and high-carbon steel.

Concurrently, the No. 3 strand was put into operation in 1982 as a continuous caster for twin slabs and triplet blooms. In order to meet the growing demand for high-cleanliness steel products, the Works reviewed the optimum length of the vertical section of the strand<sup>70)</sup> and modified the strand into a vertical bending-type continuous caster in 1991 to cast high-grade steel mainly for tinplates and automotive sheets.<sup>71, 72)</sup> Thereafter, the Works introduced to the continuous caster an electromagnetic stirrer in the mold and a tundish with an induction heater (Fig. 11) and established a technique for floating separation of nonmetallic inclusions under optimum casting temperature.<sup>73, 74)</sup> Fig. 12 shows the temperature distribution of molten steel in the tundish before and after introduction of the induction

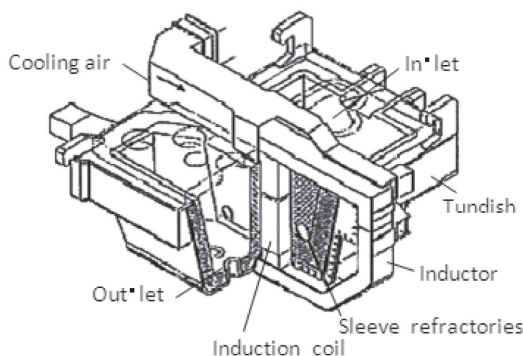


Fig. 11 Tundish with induction heater

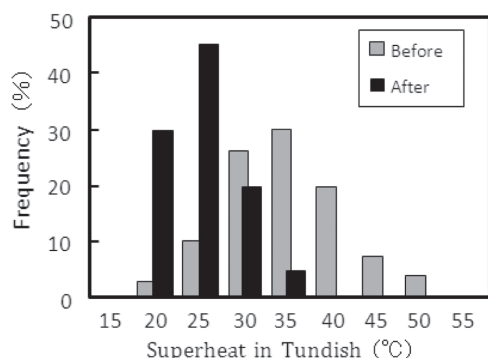


Fig. 12 Temperature drop in tundish with and without induction heating

heater.<sup>75)</sup>

In addition to the above technologies, the Works developed and applied ladle slag detection technology, technology for making the sliding nozzle filler harmless,<sup>76)</sup> and TD sealing technology as common measures to cleanse the molten steel. The Works also developed and applied stopper control technology using a solid immersion nozzle as a measure to prevent the boiling of molten steel around the immersion nozzle in the mold,<sup>77)</sup> technology for preventing the entrapment of mold flux,<sup>78, 79)</sup> and other technologies. All this has made it possible to manufacture high-grade steel sheets requiring a high degree of cleanliness.

### (3) Bloom casting technology (No. 4 strand)

The No. 4 strand was constructed in 1983 as a slab/bloom continuous caster. With one pair of rolls, it is capable of single casting, twin casting, and triplet casting of blooms and slabs of varying sizes. The casting size can easily be changed by replacing the mold and the support rolls under the mold as one unit using an overhead crane, and this allows for an efficient casting operation according to the production volume of slab and bloom.<sup>61)</sup> Fig. 13 illustrates the concept of mold construction undertaken for the No. 4 strand.

For some time after construction of the No. 4 strand, the cross section of triplet-cast blooms was as large as 320 mm by 450 mm, and those blooms were downsized at the blooming mill for the manufacturing of seamless pipes. As measures to reduce the occurrence of macrosegregation and center porosity in blooms, the Works developed a technique for securing an equiaxed microstructure through use of an electromagnetic stirrer in the upper part of the secondary cooling zone, together with the light reduction technology applicable in the horizontal section of the continuous caster,<sup>80)</sup> and thereby established technology for the dependable production of large-section blooms of high-carbon steel for rails, sheet piles, and other components.

Later on, the Works developed technology for as-cast (one-heat) casting of 220 mm sq. blooms that permits omitting the downsizing of large-section blooms. As a result, a more efficient bloom production system could be built. In particular, as a measure to provide for long-time casting operations exceeding three hours per heat, the Works introduced an induction-heated tundish (IH-TD) and developed a high-speed casting technique, thereby establishing continuous manufacturing technology. Fig. 14 shows the changes in casting time, molten steel temperature in the TD, and the heating power during triplet casting of small-section bloom.<sup>74, 75)</sup>

As a result, the continuous caster exclusive for small-section blooms of the C plant (C-BL-CC) was shut down in July 1992. That helped clear one of the hurdles to be overcome before the sole re-

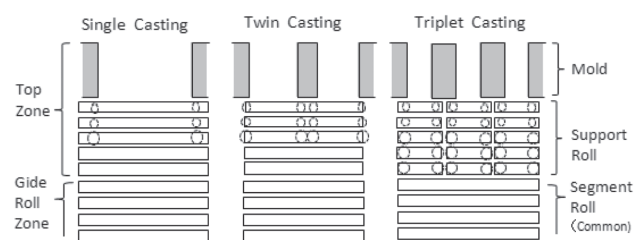


Fig. 13 Structure of mold for slab and bloom caster

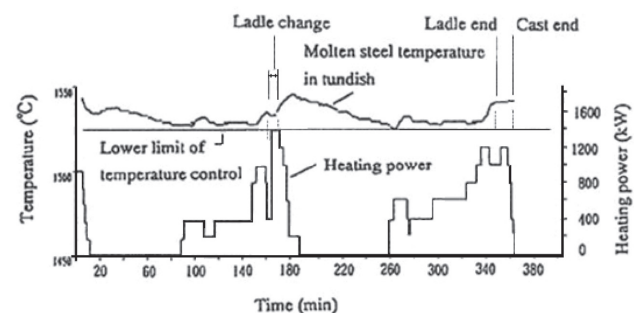


Fig. 14 Changes in temperature and heating power in tundish during triplet casting of small size bloom

maining blooming mill could be shut down.

As mentioned earlier, steels for seamless pipes are no longer manufactured by Yawata Works today since the production of seamless pipes was stopped in 2001. Even so, the bloom casting technologies that have been described above continue to support the bloom manufacturing technology of today.

## 4. Conclusion

We have described the development of Yawata Works' steelmaking processes over the past 30 years and have provided an outline of the manufacturing technologies and the developments thereof that have supported the said processes. The Works will continue progressing vigorously in order to meet increasingly sophisticated market needs as they evolve.

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