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Development of Continuous Casting Technology at Yawata Works

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Abstract:

The development of continuous casting technology at the Yawata Works is summarized in four stages: establishment of basic technology, mass production, quality improvement, and diversification. Rapid technology development after the introduction of continuous casting technology has markedly increased the continuous casting ratio. Clean steel making, direct rolling by high-speed casting, and high-quality bloom production have been adopted as three major fields of technology development. The essential points of these technologies and the ways they have been established are analyzed in detail. The development of these technologies has phased out primary mills, phased in continuous casters to be phased out, significantly raised productivity and quality, and brought about such economic benefits as energy saving. Many types of steels have been continuously cast into high-quality bloom on the casters best suited for specific properties required. Future challenges will be to rediscover means for improvement and development from among this developmental history and to create more competitive continuous casting technology.

1. Introduction

After World War II, the Japanese steel industry introduced the latest technology from Europe and the United States, strengthened competitiveness in stages through the improvement and development of field technology, and made remarkable progress in that process. Continuous casting is representative of the technologies introduced and has now reached maturity. New technology is required to accomplish still higher productivity, better quality, and lower costs. This article traces the history of continuous casting technology at the Yawata Works, discusses the steps of technological progress and intensified competitiveness, and aids the discovery of new technology as conventional technology matures.

*1 Hikari Works

2. Movements in Continuous Casting in Japan

As indicated by the curve ① in **Fig. 1**, the steel industry increased annual crude steel production from 10 million tons in about 1950 to more than 100 million tons in about 1970. Steel exports concomitantly increased and exceeded 30% of crude steel production as denoted by curve ②. Reflecting the postwar flow of steelmaking technology, first open hearths were replaced by LD converters (curve ③), then steel purity and cleanliness were enhanced by secondary refining, especially degassing, and lastly continuous casting was brought on line.

The continuous casting ratio suddenly increased in about 1972 when crude steel production reached about 100 million tons (curve ④). The first oil crisis of 1973 prompted energy-saving efforts throughout Japan and resulted in oil consumption falling 20% between 1973 to 1985. The continuous casting process achieved the effect of cutting down reheating furnace fuel consumption. The advancement of continuous casting placed new steels one after another on markets to meet the production requirements for beverage cans and automobiles, which are daily necessities nowadays. The continuous casting ratio, which was 10% in about 1970 when continuous casting was introduced in Japan, expanded to over 90% 13 years later.

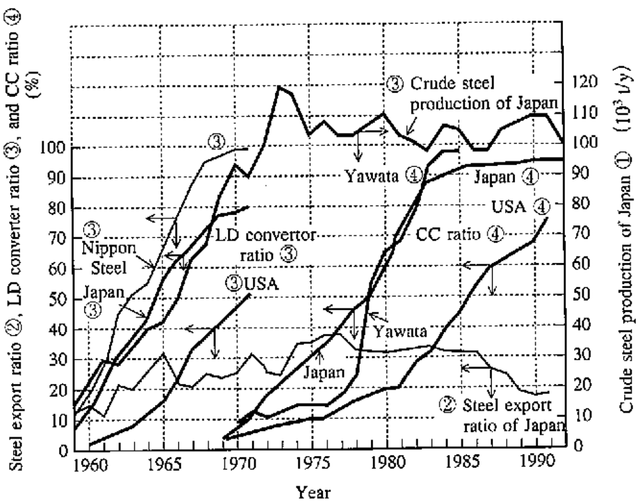

Fig. 1 Changes in indicators of steel industry and steel production

In contrast to this history of continuous casting technology in Japan, the next chapter will clarify how Nippon Steel's Yawata Works has advanced its continuous casting technology to strengthen competitiveness.

3. Discussion of Development of Continuous Casting Technology

3.1 Introduction of and changes in continuous casting technology

To clarify the progress of continuous casting technology at Yawata, the changes in continuous slab casting, continuous bloom casting, primary rolling, and continuous casting ratio from 1967 to date are summarized in **Fig. 2**. As shown in **Fig. 2**, the characteristics of these changes are described below as four periods: 1) development of basic technology for continuous casting from 1967 to 1974; 2) equipment scale-up and mass production from 1975 to 1981; 3) production efficiency and quality improvement from 1982 to 1989; and 4) quality improvement and diversification from 1990 to present.

3.1.1 Development of basic technology for continuous casting from 1967 to 1974

A stainless steel slab/bloom combination caster was installed at the Hikari Works in 1960. The technology was established by 1962 for continuously casting nickel and chromium stainless steels in 110 to 130 mm thick slabs and nickel stainless steels in 250 mm square and 200 mm round blooms[1]. Based on this experience, Nippon Steel introduced and constructed billet and slab

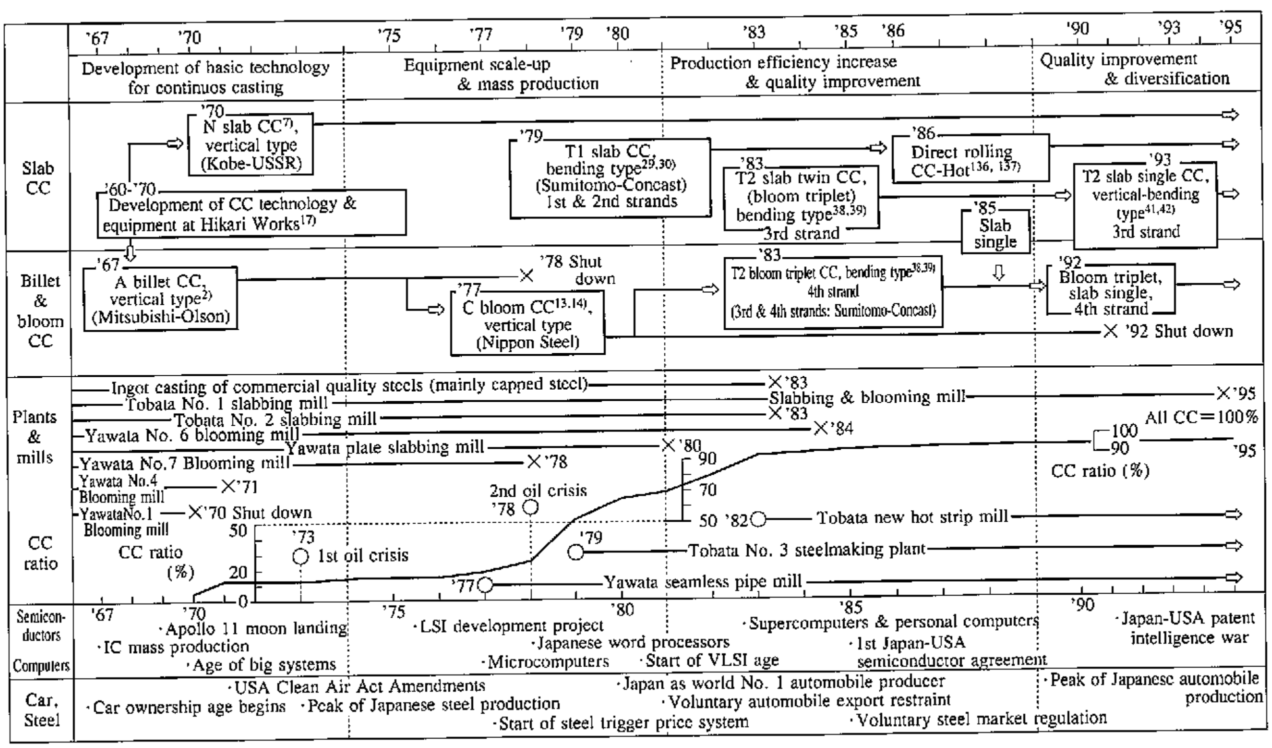

Fig. 2 Changes in continuous casting technology at Yawata Works

casters with the help of continuous caster suppliers in Japan and abroad.

Yawata's first continuous casters were two Olson vertical-bending billet casters (hereinafter referred to as the A-CC casters) built at the No. 3 steelmaking plant (equipped with 70-ton LD converters and hereinafter referred to as the A plant) in the Yawata area in 1967 and 1968[2]. The A-CC casters cast small billets, such as 80 and 100 mm square billets, in six strands and produced about 40,000 tons per month of hard wire rods, bars and spring steels, among other things[3]. Oil casting was employed. The relationship between casting methods and casting defects, such as inclusions, blowholes and segregation, and the morphology and mechanism of defects were made theoretically clear[4-6].

In 1970, a Russian vertical-type slab caster (hereinafter referred to as the N caster) at the No. 2 steelmaking plant (equipped with 170-ton LD converters and hereinafter referred to as the N plant) was constructed in the Tobata area[7,8]. The N caster produced powder cast slabs, measuring 200 or 300 mm thick and 700 to 1,800 mm wide. The casting speed ranged from 0.6 to 0.9 m/min, the monthly production volume was about 70,000 tons, and the types of steels cast included cold-rolled strip and sheet, hot-rolled strip and sheet, plates, and electrical steels. The two A casters caused the shut down of two blooming mills in the Yawata area and provided a continuous casting ratio of about 10%. The continuous casting process still experienced many quality and economic problems and therefore had not fully replaced the conventional ingot casting-primary rolling route.

3.1.2 Mass production from 1975 to 1981

The 1973 and 1978 oil crises gave impetus to energy-saving drives. The steel industry reduced reheating furnace fuel consumption with the continuous casting process. Japan's total continuous casting ratio jumped from 20% before 1973 to 60% in 1980.

Yawata's continuous casting ratio before the second oil crisis was 10%, requiring the introduction of new continuous casters with higher productivity. The Yawata Works then undertook a program to move its ironmaking and steelmaking facilities from the Yawata area near an urban district to the Tobata area where large blast furnaces were already situated. This program was designed to make environmental improvements, to enjoy the benefits of a scale-up, and to increase competitiveness[9].

Based on the technology of casting small-section billets at the A-CC casters and the results of surveys on various large-section billet casters[10-12], a 215-mm square billet caster (hereinafter referred to as the C-CC caster) was constructed at the No. 1 steelmaking plant (equipped with 150-ton LD converters and hereinafter referred to as the C plant) in the Tobata area in 1977[13,14]. The C-CC caster had a curve radius of 14 m, advantageous in flotation of inclusions, formation of equiaxed grains and prevention of internal cracks, and successfully cast 70,000 tons per month of many steels, including those for seamless pipe[15-17], shapes, wire rods, and rails.

The C-CC caster supplied high-quality blooms as tubular stock to a 17-inch seamless pipe mill built in the Yawata area in 1977[18-26]. The startup of the C-CC caster led to the closure of the A-CC casters in the Yawata area in 1978. In 1979, small-capacity refining and ingotmaking facilities were abolished at the A plant and the No. 5 steelmaking plant (equipped with 60-ton LD converters and hereinafter referred to as the L plant) in the Yawata area. In their place, 350-ton LD converters[27,28] and a 10.5-m radius concast bending-type slab caster (hereinafter referred to as the T1CC caster)[29] were built as the No. 3 steelmaking plant (hereinafter referred to as the T plant) in the Tobata area. The T1CC caster cast slabs, measuring 250 mm thick and 0.7 to 1.8 m wide, at a speed of 1.7 m/min or more, and produced more than 200,000 tons per month of strip and sheet, and electrical steels and plates, among other things[30-32].

In this way, the A and L plants and slabbing and blooming mills in the Yawata area were replaced, and the new, competitive T plant was put into operation. The technology to operate the above-mentioned mass-production casters at the C and T plants was supported by the computer technology that was making rapid progress then. The computer technology was a huge system technology using integrated circuits (ICs) and large-scale integration (LSI) and was an important technology enabling the steel industry to manage its mass production[33].

Such computer technology was studied for application in the continuous casting process as well. A practical model was developed for controlling N-CC caster[34] operations. For the T1CC caster, each slab was graded according to its quality parameters, such as the tundish steel temperature, casting speed, and mold level variation. At the same time, casting control was effected with high accuracy, and the mass production of uniform-quality slabs was successfully managed. Up to about 1977, the cost of molten steel for aluminum-killed steel continuous casting was higher than that for silicon-killed steel ingot casting. The large-scale DH vacuum degassing process[35] at the T plant enabled light treatment, improved the aluminum yield, and solved the cost problem.

The progress of mass production by continuous casting helped the Yawata Works to achieve by the end of the 1970s a continuous casting ratio of 70%, an average level in the Japanese steel industry then. In the ingot casting process, smooth-surfaced ingots were cast by coating the inside of molds with a splash repellent or using a splash container in each mold. These ingots were charged into reheating furnaces without conditioning after primary rolling, thereby reducing reheating furnace fuel consumption. Although the ingot casting-primary rolling route was at its highest possible levels of efficiency and quality, still higher operating efficiency and product quality were demanded of the continuous casting process.

3.1.3 Production efficiency and product quality improvements from 1982 to 1989

During this period, two hot strip mills in service since 1941 and 1958, respectively, were closed, and in 1982 a new hot strip mill was opened. The new hot strip mill was connected with the T plant through roller tables to allow the hot charge rolling (HCR) process whereby hot as-cast slabs can be directly charged into the reheating furnace to reduce fuel consumption. The casting technology of the T1CC caster improved to reduce slab conditioning. The HCR process came on stream in 1982 and cut energy consumption from 285,000 to 115,000 kcal/t, as shown in **Fig. 3(c)**. In pursuit of maximum energy savings, a direct rolling (DR) facility was introduced in 1987 to link the hot strip mill directly with the T1CC caster. The proximate DR process implemented at the Sakai Works was modified and applied as the remote DR process involving a steelmaking plant and a hot strip mill some distance apart[36,37]. With the introduction of high-speed slab transfer cars, the remote DR process reduced energy consumption to 47,000 kcal/t.

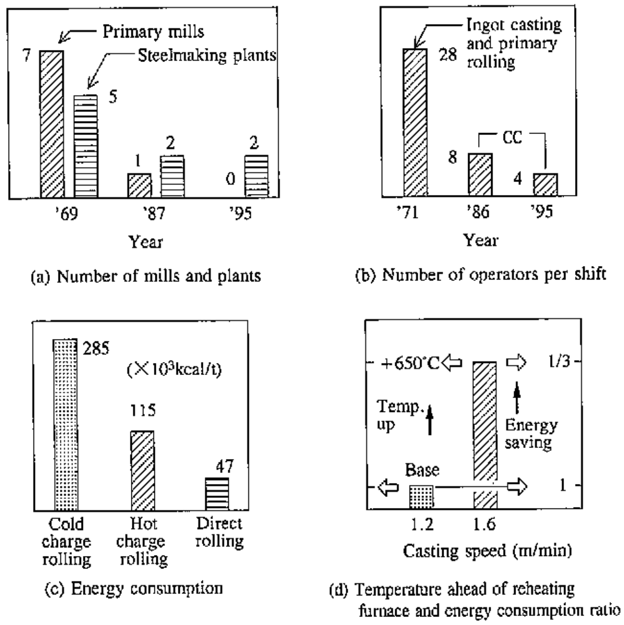

Fig. 3 Benefits of continuous casting

In the period covered, annual automobile production grew to 10 million units. Super-ultra-low-carbon (SULC) steel appeared to meet the demand of users for steel sheet with good surface appearance and high formability. To obtain a carbon content of about 50 ppm or less after vacuum degassing, the SULC steel's carbon content was decreased and its oxygen content increased at the end of blowing in the LD converter. Alumina (Al_2O_3) inclusions formed in large amounts from aluminum added as deoxidizer, making it extremely difficult to continuously cast the SULC steel. The technology to raise product quality greatly advanced by solving the problems with continuous casting of the SULC steel, as described later.

In 1983, two bending-type casters were built at the T plant to hold two slabs or three blooms simultaneously with a pair of rolls in each position, or a slab twin caster and a bloom triplet caster (hereinafter referred to as the T2CC-3st and T2CC-4st to denote the third and fourth strands following the twin-strand T1CC caster)[38,39]. Adopting the combination casters reduced construction costs and provided continuous casting with high economic efficiency. Tundish shape, roll alignment and spray nozzle arrangement in the secondary cooling zone, and other things were specially designed for the efficient combination casting of slabs and blooms.

In bloom triplet casting, a 320 mm by 450 mm rectangular section was cast, as compared with the 215 mm square section at the C-CC caster. It was divided at a blooming mill, and supplied as blooms for seamless pipe, among other products.

A 350-ton heat from the T plant, more than two times as large as a 150-ton heat at the C plant, was successfully cast in a long time of about 2 hours without appreciable temperature drop. In large-section casting, equiaxed grains were produced by electromagnetic stirring in the upper part of the secondary cooling zone, and center porosity was prevented by light reduction with convex rolls in the horizontal section. Higher than ever quality was thus achieved[40]. The progress of conventional continuous casting technology and the advent of new continuous casters resulted in the scaling down of ingot production at the N plant and caused the closure of one primary mill in the Tobata area. Scrapping and rebuilding continued to be carried out in this period as well.

3.1.4 Quality improvement and diversification from 1990 to date

This period saw annual automobile production reach 13 million units per year and beverage cans appear in large amounts on the market. Steel sheets used to make these products were of deep drawing quality but their nonmetallic inclusion content had to be reduced to the lowest possible level. The flotation of inclusions in the bending section of the T1CC caster was found to be inferior to that in a vertical-type caster. A vertical section was introduced in the T2CC-3st twin slab caster to modify it to a vertical-bending type[41-43]. An induction heater was also installed to promote the flotation of inclusions in the tundish[44,45]. The production of steels with particularly severe inclusion requirements was concentrated on this machine.

The C-CC caster for blooms was shut down in 1992, and the continuous casting of blooms for rails and seamless pipe, among other products, was transferred to the T2CC-4st caster to achieve more efficient continuous casting operations. The adoption of a 220-mm square bloom size caused temperature drop in long-time casting. The installation of a tundish steel induction heater[45] provided the stable casting for one heat in about three hours. The last primary mill in the Tobata area was closed in 1995, and the continuous casting ratio reached 100% in the 28th year since the introduction of the first continuous casters.

3.2 Benefits of continuous casting

As shown in **Fig.** 3(a), the Yawata Works had five steelmaking plants and seven primary mills in 1969 when it started continuous casting. In 1987, these plants and mills diminished to two steelmaking plants and one primary mill, and the continuous casting ratio grew to 98%. In 1985 when all steels were continuously cast, there were only two steelmaking plants and no primary mills. As shown in **Fig.** 3(b),the substitution of the continuous casting process for the ingot casting-primary rolling route cut about 20 operators from each shift. In 1995, an expert system was introduced to allow one caster to be operated by four operators per shift[46-48].

With these continuous casting and plant and mill consolidation trends, about 220 and 250 jobs were eliminated by the shutdown of the A and L plants in 1978 and 1979, respectively[9].

3.3 Technology developed to encourage switch to continuous casting

The technologies developed to strengthen competitiveness are discussed in connection with the changes since the introduction of the first continuous casters at the Yawata Works. Technology for: continuously casting clean steel slabs[49]; direct rolling slabs; and improving bloom internal quality are areas in which the author was involved. The expansion in the number of continuously cast steels (slabs) because of these technologies is also described.

3.3.1 Continuous casting of clean steel slabs

The main clean steel continuous casting technologies established to date at Yawata are shown in **Fig. 4**, and their changes are summarized in **Fig.** 5. According to the two figures, elementary technologies from the ladle through the tundish to the mold are described. In addition, cast steel quality evaluation technology

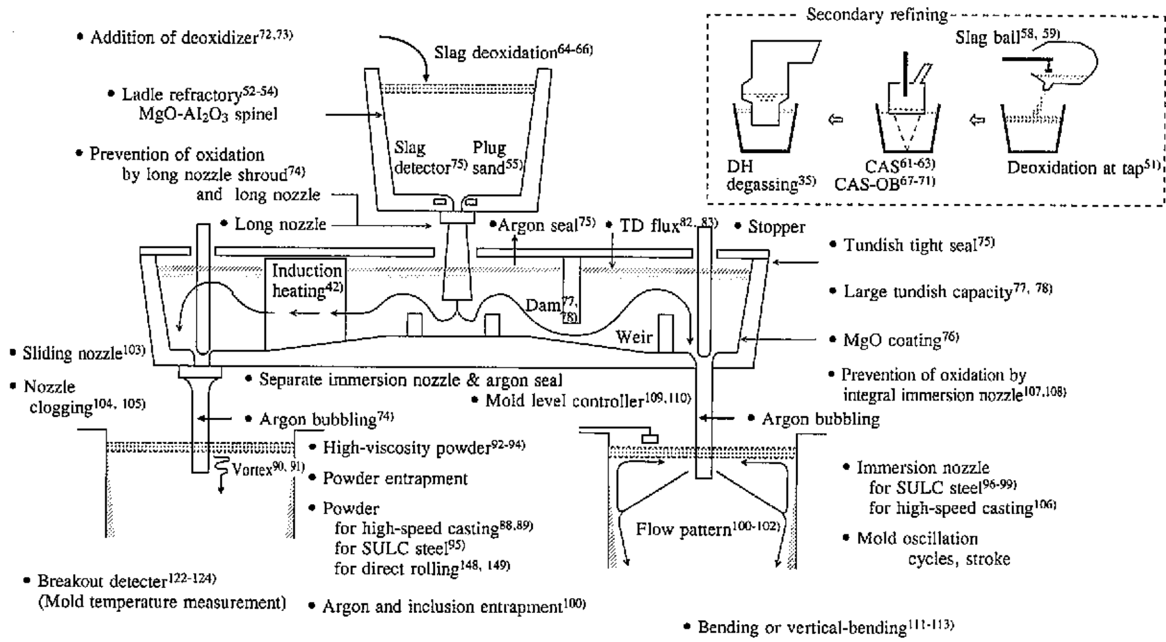

Fig. 4 Composition of continuous casting technologies from ladle to mold at Yawata Works

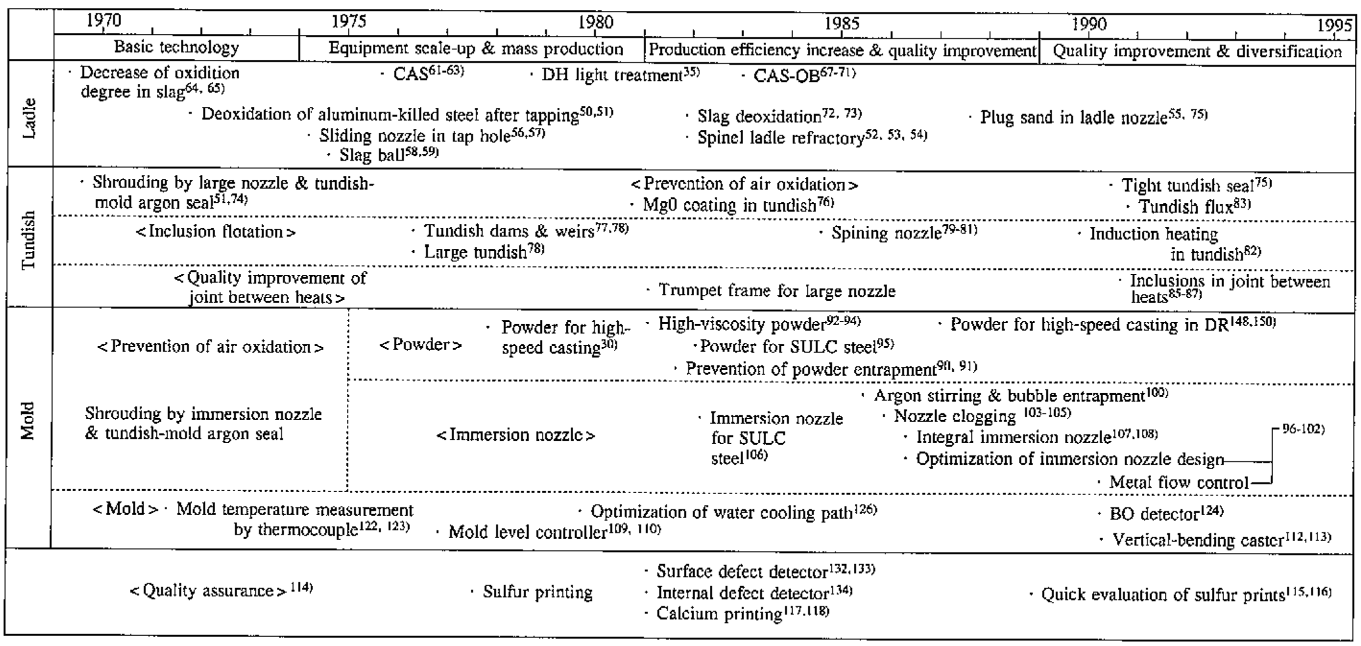

Fig. 5 Changes in clean steel making technologies at Yawata Works

and deep drawing quality steel sheet market expansion are discussed.

(1) Ladle refining

With ladle refining, the control of the molten steel oxygen content and the slag oxygen content is essential to produce clean steel slabs.

(i) Molten steel oxygen control

One primary problem from 1970 to 1973 was the optimization of the deoxidation process for aluminum-killed steel to be continuously cast[50]. In actual steelmaking operations, the oxygen content of molten steel was estimated by taking the product of the end-point carbon and manganese contents as parameters. Aluminum was then added to provide an oxygen content of about 45 ppm at an aluminum content of 0.056% after deoxidation. The aluminum-killed steel was thus stably cast continuously[51]. In 1982, conventional silica (SiO_2)-bearing semi zircon brick was replaced by alumina-spinel neutral brick to reduce the supply of oxygen from the lade lining refractory to the molten steel. This change increased the aluminum yield and decreased the formation of alumina inclusions[52-54]. To prevent molten steel oxidation by silica-base plug sand for self-opening ladles, an alumina-base plug sand was used with good results[55].

(ii) Slag oxygen control

Attempts were made to develop technology to prevent alumina forming from the reaction of added aluminum with ferrous oxide (FeO) in slag. The first attempt involved reducing the volume of carryover slag from the LD converter into the ladle. In 1975, work was undertaken to develop slag cutting technology for tapping. A sliding nozzle adopted on ladles was installed in LD converter and tested for its ability to stop slag carryover into the ladle during tapping[56,57]. Refractory wear control was difficult, and the sliding nozzle technology was not practically applied. The slag ball method was then developed[58,59]. This method reduced the ladle slag layer thickness from more than 150 mm to about 45 mm, improving the aluminum addition yield from 20 to 30%. The method of drawing slag out of the ladle with a siphon was studied, but was not employed for production[60].

As the method of preventing contact between the slag and aluminum, the CAS process[61-63] was developed on the basis of studies on the oxidation degree of slag[64-66] conducted in 1976. In the CAS process, argon is blown through the bottom of a ladle, a large refractory tube is immersed into the molten steel surface from which slag is removed by the bottom-injected argon, and aluminum is added through the tube without contacting the slag. The CAS process reduced aluminum consumption by 25% for low-carbon aluminum-killed steel and by 30% for aluminum-silicon-killed steel. It was found to reduce alumina inclusion formation and to improve cast steel quality. In 1985, the CAS-OB process[67-71] was developed for top blowing oxygen into a ladle of molten steel and heating the molten steel. When a heat is returned from a continuous caster because of a continuous caster accident, it can be reheated by the CAS-OB process and then treated by the CAS process to promote the flotation of inclusions and to obtain the same quality as ordinary heats.

In 1979, a light treatment process was adopted on a new large DH vacuum degasser at the T plant. The steel oxygen content was 30 ppm maximum after vacuum degassing and 20 ppm maximum in the continuos caster tundish, resulting in a sharp decrease in the number of slivers in strip and sheet products. The addition of lime and an aluminum-bearing modifier to slag immediately after tapping was established as technology for reducing ferrous iron (FeO) activity in the slag[72,73]. The technology cut slag FeO content to 4% or less, lowered the incidence of product slivers, and improved product quality.

(2) Tundish

The main items of technology development concerning the tundish are: i) prevention of molten steel oxidation; ii) flotation, adsorption and removal of inclusions in the tundish; and iii) reduction of inclusions in joints between heats.

(i) Prevention of molten steel oxidation

The first important technology to be developed was non oxidation casting. In about 1971, a method was established to stop molten steel oxidation by installing nozzles between the ladle and tundish and between the tundish and mold. These were designed to shroud the pouring stream from air and to inject argon into nozzle joints[74]. This technology was extremely effective in greatly reducing the formation of alumina inclusions by oxidation and allowed the continuous casting of aluminum-killed steel used to produce tinplate and other high-grade strip and sheet products. In 1975, a method involving injecting argon into the tundish was developed to prevent molten steel oxidation in the tundish. In 1990, this technology was upgraded to that of tightly covering the tundish and sealing the joint between the cover and tundish with argon[75].

In 1982, the tundish refractory surface coating material was changed from ZrO_2 to MgO to prevent the oxidation of molten steel by the coating material[76]. These techniques enabled the stable production of deep-drawing sheets of low-carbon and ultralow-carbon steels in particular.

(ii) Flotation and adsorption of inclusions

In 1979, a 60-ton tundish was adopted on the T1CC caster to replace the N-CC caster's 15-ton tundish. This was to promote inclusion flotation by increasing the residence time of molten steel in the tundish. The tundish was shaped like a ship and provided a direct stream from the ladle to the mold. For this reason, dams and weirs were installed in two or more positions to aid in inclusion flotation[77,78]. In 1986, a spinning nozzle was introduced as an effective tool for promoting inclusion flotation by blowing stirring gas, but it was not regularly adopted due to high refractory costs[79-81].

A high tundish temperature proved to encourage inclusion flotation, but this accelerated ladle and tundish refractory wear. In 1991, technology was established for enlarging inclusions at an optimum molten steel temperature and promoting their flotation by introducing an induction heating and stirring unit[42]. At the same time, a method was adopted for adding a flux to the surface of molten steel in the tundish to adsorb floating inclusions[82,83].

(iii) Reduction in inclusions in joints between heats

To improve productivity, the number of sequence-cast heats increased[84], raising the number of joints between heats. Such joints were found to contain large amounts of inclusions arising from the slag carried over from the ladle. Many improvements were made to solve this problem[85-87]. In 1982, the long nozzle of each ladle in sequence casting was opened and submerged. This nozzle opening method proved effective in starting a sequence cast stream without entrapping the slag in the tundish.

The timing of slag carryover from the ladle into the tundish was determined by observing conditions within the tundish. The sliding nozzle was closed after the slag was seen to flow into the tundish. In 1993, a method was commercialized for installing a coil in the nozzle of a ladle, detecting an electrical signal produced by slag carryover from the ladle, and closing the sliding nozzle at the electrical signal. This method halved the slag carryover from the ladle into the tundish[75].

(3) Mold

Key mold technologies for the production of clean steel were: 1) powder; 2) immersion nozzle; 3) mold level control; and 4) vertical section retrofitted on a bending-type caster.

(i) Powder

In 1979, development started on a high-speed casting powder at the T1CC caster[88,89]. When surface defects in sheet slabs cast at high speed were analyzed by electron microscopy in 1982, powder components were found and presumed to have resulted from the entrapment of molten powder on the surface of molten steel in the mold. The phenomenon of powder entrapment in the mold was clarified in detail to develop corrective measures[90,91]. The flow velocity of the molten steel surface on which rides a molten powder layer was reduced below a critical value. The use of a high-viscosity powder commenced on site[92-94]. A powder that was low in carbon content and capable of providing a molten powder layer of uniform thickness was developed and exploited to prevent the pickup of carbon in the mold when continuously casting SULC steel[95].

(ii) Immersion nozzle

When alumina precipitates and clogs the immersion nozzle, aluminum-killed steel can no longer be cast continuously. This blockage was prevented by injecting a small amount of argon into the immersion nozzle. Argon was found to raise inclusions in the mold, but it was also made clear that large amounts of argon were entrapped as bubbles in the slab. An optimum argon injection rate was determined accordingly.

The angle and shape of molten steel discharge ports in the immersion nozzle were optimized to prevent the entrapment of argon[96-99]. The flow of molten steel in the mold was theoretically clarified using a water model, and the results obtained were used to determine the optimum design of the immersion nozzle[100-102]. Work advanced to develop plug-free nozzle materials[103]. A new material consisting of alumina and graphite with an addition of zircon was effective against clogging[104,105]. Similar to a mold powder, an immersion nozzle with low carbon pickup was developed for continuously casting SULC steel[106]. The immersion nozzle was changed from the separate type to the integral type to completely eliminate air entrapment and to more effectively prevent the air oxidation of molten steel[107,108].

(iii) Mold level controller

Until about 1979, an electromagnetic mold level controller sensor was installed above the mold proper[109]. When such a sensor was installed separately from the mold at the middle of the mold thickness and at one quarter of the mold width, and a proportional-integral-derivative (PDI) control was also introduced, the resultant mold level controller increased in accuracy, controlling the mold level within three mm of the maximum fluctuation width, and preventing mold powder entrapment[110].

(iv) Introduction of vertical section

Despite the implementation of various measures as noted above, the accumulation of inclusions in the bending section of bending-type continuous casters was a fundamental problem[111]. The relationship between vertical section length and inclusion flotation was studied, and it was clear that the vertical section would be fully effective in inclusion flotation if it was 2.5 m or more[112,113]. In 1991, the T2CC-3st caster was retrofitted with a 2.5-m long vertical section and used to produce low-carbon aluminum-killed steel for high-grade tin plate and deep drawing quality steel such as automotive SULC steel[42].

(4) Continuously cast steel quality evaluation

(i) Inclusion judgment

The above-mentioned technological improvements were introduced while investigating product defects by electron microscopy and identifying responsible constituents. Mold powder was blamed for sodium defects, slag for calcium, silicon and magnesium defects, and alumina for alumina defects. Using a computerized production control system, a continuously cast slab number was determined from a cold-rolled coil number. The casting conditions of the slab were analyzed from records of variations and troubles in such factors as the tundish steel temperature, mold level and casting speed at the positions of defects in the slab. A true cause for each defect was clarified, and each necessary technological improvement was undertaken.

(ii) Quality assurance

Technology was also developed for more accurately evaluating slab quality and supplying high-quality slabs to the rolling process[114]. From 1979, the T-CC caster started using sulfur printing for establishing criteria for the position and number of internal cracks as well as alumina and other inclusions, argon blowholes in the slabs, and for grading the slabs according to their quality levels thus determined[115,116]. A calcium printing method that can evaluate slag and other calcium inclusions was also developed and implemented[117,118].

(5) Expansion of markets for deep drawing quality products

The aforementioned clean steel production measures have reduced the size of inclusions in continuously cast steels from about 250 μm in 1970 to about 50 μm at present. Bodies of drawn and ironed (DI) beverage cans are deep drawn and fitted with an end. The incidence of cracks in the flange ironed further to fit the end has diminished from 100 ppm in about 1980 to one-tenth of that now. As a result of these improvements, Japan's total DI can production reached 5 billion in 1970[119]. Automotive steel sheets made from SULC steel vacuum degassed to very low carbon and nitrogen levels to facilitate deep drawing were guaranteed a beautiful surface appearance by increased slab steel cleanliness and were mass-produced by continuous casting. The sheet steel cost of popular cars consequently dropped to between 1.2 to 1.8 yen/g[120].

3.3.2 Direct rolling (DR)

Since its introduction, the continuous casting process has boosted production capacity. Technologies developed for breakout prevention, sequence casting, and high-speed casting culminated in the creation of the direct rolling (DR) process in 1986. The direct rolling process dramatically improved the production capacity between the continuous casting and hot rolling processes. This technological progress is reviewed next.

(1) Breakout prevention

Breakout prevention is indispensable for the high-speed casting of slabs. The phenomena taking place in the mold had to be clarified first. In 1973, many thermocouples were buried in the wide and narrow faces of the mold at the N-CC caster and used to investigate the heat transfer characteristics of the mold. The relationship between mold face taper, powder properties and heat removal and the effect of air gap between the strand and mold were invesitgated[121-123]. According to the findings obtained, optimum casting conditions were determined to achieve stable caster operations.

Based on the above results, the basic idea of breakout prediction with thermocouples embedded in the mold, which is widely adopted now, was conceived. This method was adopted on the high-speed bending-type caster at the T plant and proved effective in breakout prevention. Along with the progress of computer technology, in 1991 a neurocomputer was used to enhance the detection accuracy of sticking-type breakouts[124]. A breakout prediction unit using an accelerator was developed, but is not used now because of such problems as sensitivity to miscellaneous vibrations around the mold. Cooling water channels in the mold copper plates were improved in construction to boost mold heat conduction during high-speed casting[125,126].

(2) Sequence casting

In 1974, the N-CC caster sequence cast heats by stopping the slab of the previous heat in the secondary cooling zone, inserting a connecting block in the molten steel in the mold, sealing the gap between the mold and block by adjusting the mold width, and casting the next heat[127]. Using this practice, a sequence cast of 186 heats was accomplished in about 240 hours, a world record then. This is the basis for today's mold width changing technology. In 1979, a flying mold width changing unit was introduced at the T1CC caster and markedly improved caster production capacity[31].

(3) High-speed casting and hot charge rolling (HCR)

High-speed casting reduces the flow of molten powder in the mold, rapidly cools the strand, and increases the frequency of stand surface cracks. Mold powders with optimum viscosity or basicity against these problems were selected according to the results of field tests[30]. Internal cracks were found to result from strand bulging[128], and improper roll gap was identified as one cause. A roll gap measuring device was developed as a corrective measure and was useful in preventing internal cracks[129,130]. A sulfur printing method was developed for locating internal cracks in slabs, calculating internal strains from the internal crack positions, and adopting an optimum secondary cooling pattern to meet the properties of each type of steel to be cast. This method stopped internal cracks occuring[131].

Tapping these technologies, the T1CC caster achieved high-speed casting at 1.7 m/min or more in three months after its start-up in 1979 and began hot charge rolling in 1983. The hot charge rolling process used instruments to guarantee cracking at less than allowable limits, including an eddy-current tester (ECT)[132] for detecting edge cracks according to magnetic flux changes, a laser scanning tester (LST)[133] for locating longitudinal cracks at the midwidth of the strand, and a ultrasonic tester (UST)[134] for finding central cracks in the strand. With the subsequent rapid development of quality building technologies, these instruments became redundant and were not used in the direct rolling (DR) process described next.

(4) Direct rolling (DR)

As noted above, high-speed casting improved to produce defect-free slabs. In 1986, direct rolling was implemented at the T1CC caster[135-138]. Because slabs must be hot enough to be direct rolled, it was a challenge to raise the temperature of the entire strand and to compensate for the temperature of the strand edges subject to especially large temperature drops. The following measures were undertaken.

First, mist cooling[139] was introduced to cool the strand mildly in the bending section of the continuous caster. The strand edges were not cooled. The strand edges were insulated with covers in the horizontal section of the caster, and the crater end was extended to the end of the caster to reheat the strand with the heat of the liquid core[140]. Liquid-core reheating eliminated strand cooling, but deflected support rolls. Grooved rolls alone were cooled to solve the deflection problem[141,142]. At the exit of the caster, the strand surface temperature was about 1,240°C at the midwidth and 1,020°C at the edges[143].

After the cutter, the slab edges were heated with luminous wall burners[144,145]. Each slab was then transferred into the slab transfer car's high-temperature insulating box and carried for about three minutes over a distance of 470 m to the entrance of a hot strip mill. As shown in **Fig. 6**, the required time to pass from the mold of the caster to the entrance of the hot strip mill was about 52 minutes, far shorter than about eight hours for the conventional HCR process. In front of the rough rolling train, the slab was charged into a gas-fired edge heater and held there for

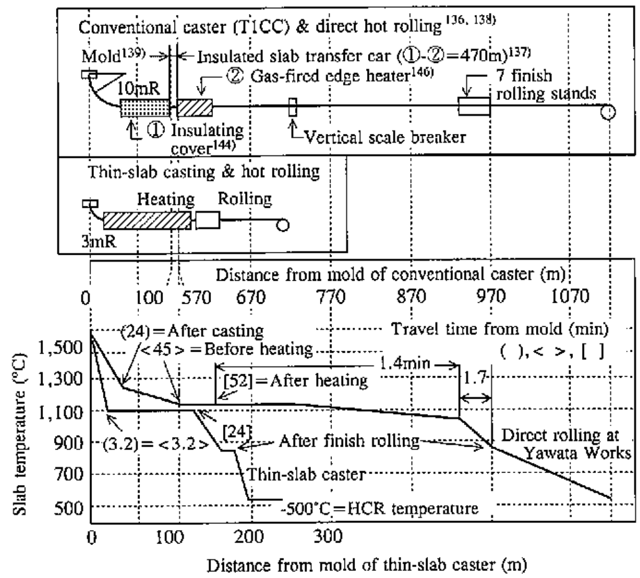

Fig. 6 Temperature change in direct rolling process at Yawata Works

about seven minutes, discharged with a midwidth temperature of about 1,120°C and an edge temperature of 1,080°C, and fed into the rough rolling train[146]. As also shown in **Fig. 6**, the thin-slab casting process that has come into the spotlight in recent years exhibits temperature changes much smaller than those of the Yawata Works' direct rolling process and is considered as the ultimate form of direct rolling.

The above-mentioned technologies made it possible to hold the strand edges at or above 900°C to prevent the precipitation of aluminum nitride (AlN), and to control the grain size of aluminum-killed steel. Direct rolling required slabs with fewer surface and internal defects — the most stringent quality levels to date. The thickness of scale formed in the reheating furnace was about 1.35 mm for the hot charge rolling process. With the direct rolling process, slabs only had 0.6 mm of scale because they bypassed the reheating furnace, and subsurface defects, such as powder and alumina inclusions, cracks, and pinholes, remained as flaws in hot-rolled strip and sheet. In particular, powder inclusions were found to be rolled into surface defects in cold-rolled strip and sheet products. A powder of such a high solidification temperature that it was removed from the strand surfaces by water sprays in the secondary cooling zone of the continuous caster was used with good results.

Against the loss of slab strength at elevated temperatures, hot slabs free of internal cracks were produced by mild air mist cooling to the extent that bulging did not occur in the bending section. Roll deflection in the horizontal section caused center segregation. This problem was solved by using grooved rolls as already described and by cooling. Direct rolling thus became feasible also for high-grade products, including low-carbon cold-rolled, hot-rolled, and coated strip and sheet[147-149].

3.3.3 Improvement in internal quality of blooms

Among internal cracks in continuously cast billets and blooms are segregation and porosity at the cross-sectional center. **Fig. 7** summarizes the changes in measures implemented against center segregation and porosity. For center segregation, electromagnetic stirrer testing was applied in 1972 to hard steel wire billets at the A plant in the Yawata area. Optimum operating conditions, such as frequency, current and rotating method, were determined[150,151]. Based on these test results, in 1977 two electromagnetic stirrers (EMSs) were installed in the top part of the secondary cooling zone, or three and eight m below the mold, on the large caster C-CC with a bending radius of 14 m at the C plant during the continuous casting of 180 to 340 mm square blooms. These reduced center segregation by increasing equiaxed grains[152]. In-mold electromagnetic stirring was also found to be effective, but was not commercialized[153-155].

In 1983, two electromagnetic stirrers were installed in the top part of the secondary cooling zone, or 4.1 and 10.3 m below the mold, at the 320 by 450 mm bloom caster T2CC-4st at the T plant. They improved center segregation, but not center porosity. Center porosity was presumed to occur because the crater end moved apart as much as 12 m from the unbending point in the horizontal section of the caster. The method of slightly bulging the strand and then reducing the strand (called the RIB-CAST process) was developed as one solution[156]. The RIB-CAST process decreased center porosity, but increased internal cracks. An alternative process, called the convex roll process, was developed that slightly reduces the strand with convex rolls, instead of bulging the strand. The convex roll process prevented center porosity formation and significantly reduced center segregation[157]. The bloom size varies with the type of steel, such as for rails and seamless pipe. It was clear that there was an optimum convex roll width for a specific bloom shape. Slight reductions with high efficiency became feasible, and center porosity was prevented by a contraction of about 6 to 7 mm[158-162].

Technology development for continuous bloom casting was relentlessly pursued as discussed above. Compared with 80 and 100 mm square billets used in 1967, about 15 to 20 times larger blooms can be now continuously cast, as shown in **Fig. 7**. Many types of steels can also be continuously cast into blooms, such as wire rods, bars, shapes, and seamless pipe and rails with stringent quality requirements. Blooms were continuously cast for rails for trains running at high speeds of 200 to 250 km, as represented by the Shinkansen ("bullet train").

3.3.4 Expansion of steel types continuously cast into slabs

Fig. 8 shows the way in which the continuous slab casting of various steels was concentrated on casters of high efficiency based on the technologies described previously. In 1970, slabs for: tin plate with strict inclusion requirements; coated, cold-rolled and hot-rolled sheet products; and pipe were continuously cast in aluminum-killed steel at the N-CC caster[51]. These slabs were cast at high speeds on the T1CC caster in 1979 and were eventually direct rolled.

Slabs of low-carbon aluminum-killed steel for DI cans, for example, and of super-ultra-low-carbon (SULC) steel for deep-drawn parts were initially cast on the vertical-type caster N-CC in about 1985. In 1993, these slabs were cast on the T2CC caster, meeting the two objectives of improved production efficiency and quality, and reinforcing the competitiveness of the Yawata Works. The continuous casting of plate slabs commenced at the casters N-CC[163] and T1CC in 1970. At the N-CC caster, center segregation was prevented by such measures as mild mist cooling, tundish hoop addition, low-temperature casting, and ultralow-speed casting. The result was high-grade plate slabs[164-169]. To attain greater competitiveness, the continuous casting of these

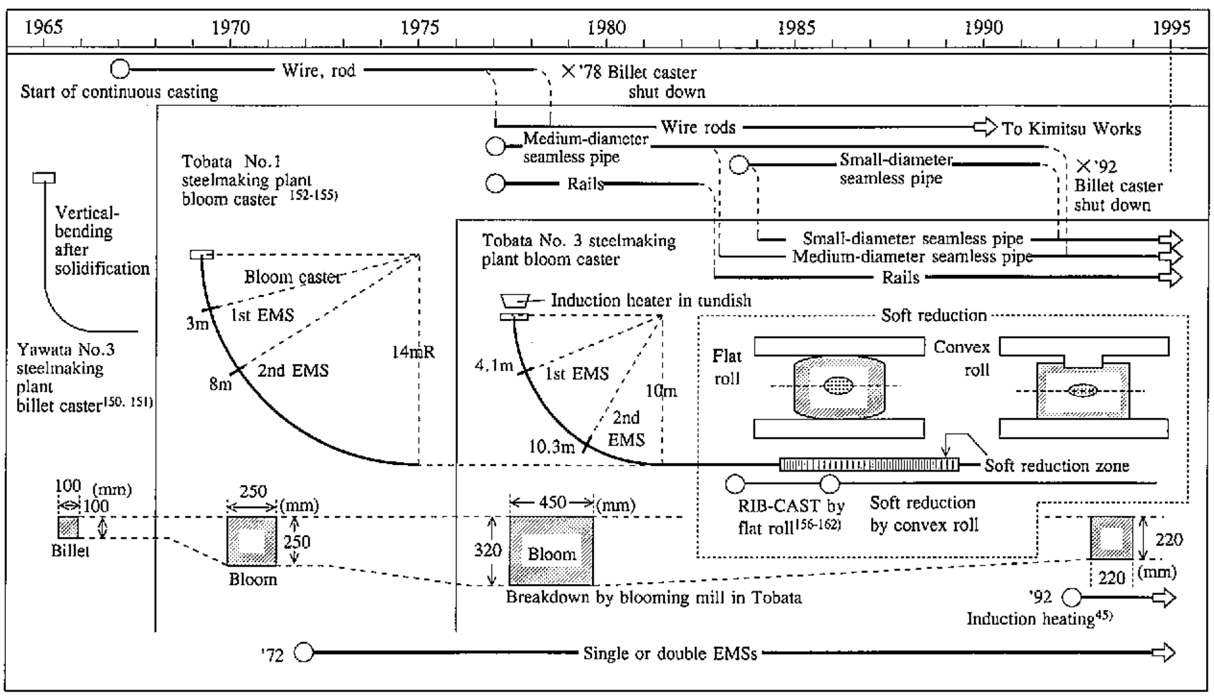

Fig. 7 Changes in technologies for improving internal quality of blooms at Yawata Works

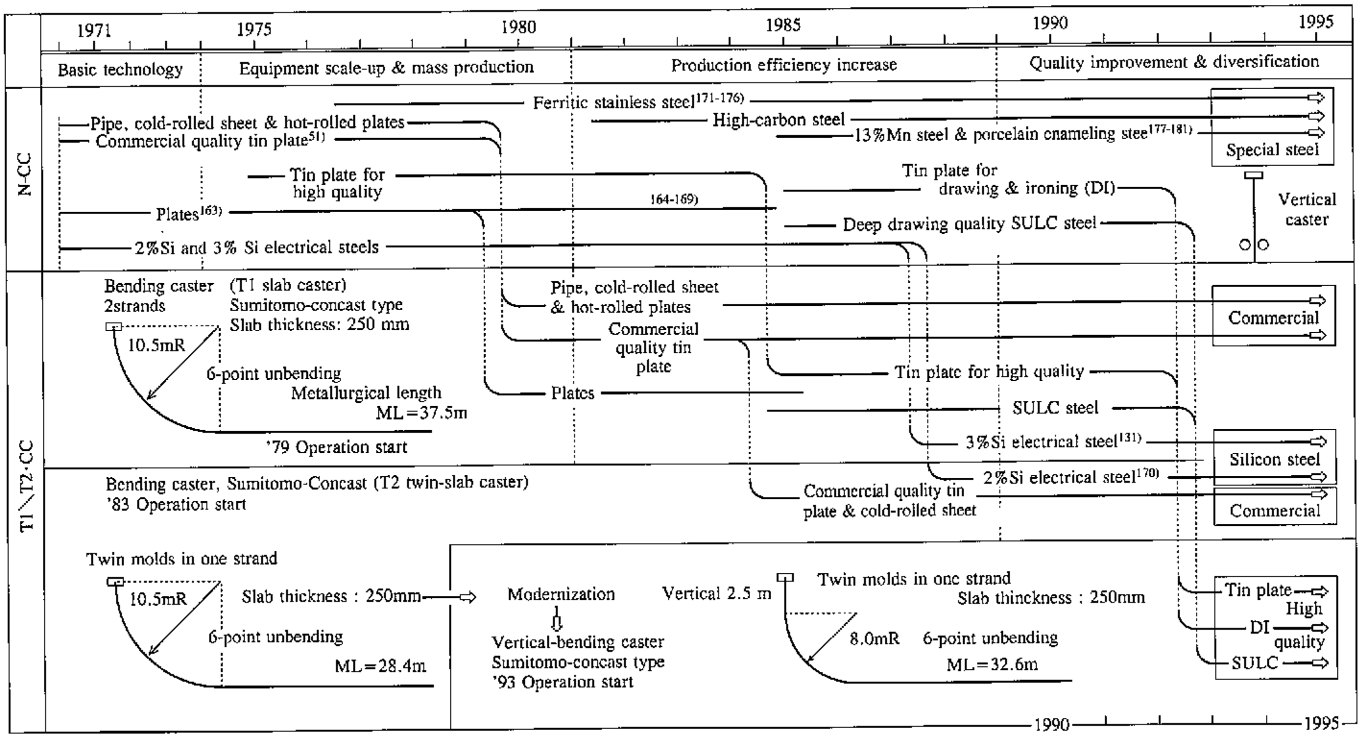

Fig. 8 Changes in continuously cast steels and continuous casters at Yawata Works

slabs was transferred to mass-production plants at the Kimitsu and Oita works.

For electrical steels, first 2% silicon steel and then 3% silicon steel were continuously cast. In about 1987, electrical steel slabs were continuously cast at the T1CC and T2CC-4st casters to meet increased production of electrical steels. The 2% silicon steel was cast at the high speed of 1.2 m/min on the T2CC-4st caster. These slabs developed columnar grains and ridging resulted when rolled into product. As a corrective measure, electromagnetic stirring was applied to increase equiaxed grains frequency and to prevent ridging[170]. The 3% silicon steel is wider in the mushy region and more susceptible to internal cracking than carbon steels. With its secondary cooling pattern optimized to prevent internal cracking, the 3% silicon steel was continuously cast at the high speed of 1.5 to 1.7 m/min at the T1CC caster. As electrical steel slabs were continuously cast at higher speed and temperature in this way, their charging temperature into reheating furnaces was raised accordingly. As shown in **Fig.** 3(d), the energy required to produce 3% silicon steel dropped to one-third of the previous level[131]. In 1977, stainless steels and ferritic grades, previously produced by the ingot casting-slabbing process in the Yawata area, were then continuously cast into slabs at the N-CC caster. An electromagnetic stirrer was installed just below the mold to obtain 60% or more equiaxed grains to prevent ridging[171-173]. Improvement in surface quality made it possible to eliminate conditioning for continuously cast slabs[174-176].

High-carbon steel transferred from the Muroran Works was sensitive to internal cracking and had severe inclusion requirements. In 1987, continuous casting of this material started at the N-CC caster to achieve low-speed casting on a vertical-type machine and to provide better quality. Following these changes, high-grade strip and sheet steels, including low-carbon aluminum-killed steel for tin plate and super-ultralow-carbon (SULC) steel, are continuously cast on the vertical-bending caster T2CC-3st. Other strip and sheet steels and electrical steels are continuously cast on the bending-type casters T1CC and T2CC-4st. The bending-type caster N-CC produces high-carbon steels, ferritic stainless steels and 13% manganese steel[177]. It also produces specialty steels[178-180], such as porcelain enameling sheet steel[181] and 20% chromium-5% aluminum steel[178-180], using additions of special element wires into the mold.

The accumulation of technologies developed has expanded the types of steels that can be continuously cast. The competitiveness of the Yawata Works was reinforced by selecting the caster best suited for a particular steel in terms of productivity, quality and cost and by continuously casting the steel on that caster.

4. Conclusions

Nippon Steel's Yawata Works has added new technologies of its own to continuous casting technologies introduced from outside the Company. Nippon Steel has acquired cost reductions, quality improvements and increased productivity thanks to the continuous casting process. These factors have boosted competitiveness. Future challenge will be to discover further hints for improvement from the development history of continuous casting technologies reported here, and to create more competitive continuous casting technologies.

References

1) Watanabe, A. et al.: Seitetsu Kenkyu. (261), 3 (1967)
2) Steelmaking Committee, ISIJ: Private communication. March 1969
3) Steelmaking Committee, ISIJ: Private communication. November 1972
4) Mori, H. et al.: Tetsu-to-Haganė. 57, 263 (1971)

5) Mori, H. et al.: Tetsu-to-Hagané. 56, 1824 (1970)
6) Mori, H. et al.: Tetsu-to-Hagané. 57, 1500 (1971)
7) Steelmaking Committee, ISIJ: Private communication. December 1970
8) Steelmaking Committee, ISIJ: Private communication. March 1978
9) Eighty-Year History of Yawata Works — Divisional History. Volume I, p. 113, and Volume II, p. 456
10) Miyamura, K. et al.: Tetsu-to-Hagané. 62, S482 (1976)
11) Miyamura, K. et al.: Tetsu-to-Hagané. 63, S92 (1977)
12) Kaneko, N. et al.: Tetsu-to-Hagané. 63, S153 (1977)
13) Nishiwaki, M. et al.: Tetsu-to-Hagané. 64, S204 (1978)
14) Steelmaking Committee, ISIJ: Private communication. November 1977
15) Uchida, Y. et al.: Tetsu-to-Hagané. 66, S246 (1980)
16) Miyamura, K. et al.: Tetsu-to-Hagané. 72, S283 (1986)
17) Koga, N. et al.: Tetsu-to-Hagané. 72, S1083 (1986)
18) Kanemaru, K. et al.: Tetsu-to-Hagané. 66, S186 (1980)
19) Kanemaru, K. et al.: Tetsu-to-Hagané. 69, S154 (1983)
20) Kaneko, N. et al.: Tetsu-to-Hagané. 64, S205 (1978)
21) Kusano, A. et al.: Tetsu-to-Hagané. 68, S993 (1982)
22) Miyamura, K. et al.: 65, S229 (1979)
23) Steelmaking Committee, ISIJ: Private communication. October 1978
24) Steelmaking Committee, ISIJ: Private communication. March 1979
25) Steelmaking Committee, ISIJ: Private communication. July 1986
26) Yamaji, K. et al.: CAMP-ISIJ. 6, 287 (1993)
27) Nakagawa, H. et al.: Tetsu-to-Hagané. 66, S249 (1980)
28) Steelmaking Committee, ISIJ: Private communication. July 1979
29) Harabuchi, T. et al.: Tetsu-to-Hagané. 66, S251 (1980)
30) Steelmaking Committee, ISIJ: Private communication. November 1980
31) Steelmaking Committee, ISIJ: Private communication. October 1982
32) Minami, K. et al.: Tetsu-to-Hagané. 67, S169 (1981)
33) Nakayama, S.: Asahi Sensho 297 "Japan's Technological Capabilities: Postwar History and Future Outlooks." p. 104
34) Iwao, N. et al.: Tetsu-to-Hagané. 63, S616 (1977)
35) Ouji, M. et al.: Tetsu-to-Hagané. 66, S250 (1980)
36) Tsubakihara, O. et al.: Tetsu-to-Hagané. 72, A167 (1986)
37) Steelmaking Committee, ISIJ: Private communication. March 1988
38) Tanaka, I. et al.: Tetsu-to-Hagané. 69, S982 (1983)
39) Steelmaking Committee, ISIJ: Private communication. July 1983
40) Steelmaking Committee, ISIJ: Private communication. July 1984
41) Nishihara, R. et al.: CAMP-ISIJ. 5, 1342 (1992)
42) Konishi, J. et al.: CAMP-ISIJ. 5, 1343 (1992)
43) Steelmaking Committee, ISIJ: Private communication. September 1992
44) Miura, R. et al.: Tetsu-to-Hagané. 81, T30 (1995)
45) Steelmaking Committee, ISIJ: Private communication. September 1993
46) Shimokasa, T. et al.: CAMP-ISIJ. 8, 256 (1995)
47) Murayama, M. et al.: CAMP-ISIJ. 4, 1296 (1991)
48) Steelmaking Committee, ISIJ: Private communication. September 1994
49) Steelmaking Committee, ISIJ: Private communication. July 1985
50) Okohira, K. et al.: Tetsu-to-Hagané. 59, 1166 (1973)
51) Steelmaking Committee, ISIJ: Private communication. March 1973
52) Tanaka, H. et al.: Tetsu-to-Hagané. 69, S220 (1983)
53) Shimada, Y. et al.: Tetsu-to-Hagané. 71, S230 (1985)
54) Shimada, Y. et al.: Tetsu-to-Hagané. 73, S172 (1987)
55) Tanaka, H. et al.: CAMP-ISIJ. 5, 303 (1992)
56) Sakamoto, M. et al.: Tetsu-to-Hagané. 61, S122 (1975)
57) Steelmaking Committee, ISIJ: Private communication. March 1978
58) Ouji, M. et al.: Tetsu-to-Hagané. 63, S130 (1977)
59) Steelmaking Committee, ISIJ: Private communication. March 1977
60) Yukawa, T. et al.: Tetsu-to-Hagané. 61, S124 (1975)
61) Haraguchi, H. et al.: Tetsu-to-Hagané. 61, S135 (1975)
62) Sato, N. et al.: Tetsu-to-Hagané. 64, S638 (1978)
63) Steelmaking Committee, ISIJ: Private communication. July 1978
64) Mori, H. et al.: Tetsu-to-Hagané. 59, S461 (1973)
65) Okohira, K. et al.: Tetsu-to-Hagané. 60, 192 (1974)
66) Steelmaking Committee, ISIJ: Private communication. November 1972
67) Aoki, H. et al.: Tetsu-to-Hagané. 71, S1086 (1985)
68) Aoki, H. et al.: Tetsu-to-Hagané. 72, S1100 (1986)
69) Takahashi, T. et al.: Tetsu-to-Hagané. 72, S244 (1986)
70) Steelmaking Committee, ISIJ: Private communication. March 1985
71) Steelmaking Committee, ISIJ: Private communication. March 1986
72) Hongu, A. et al.: Tetsu-to-Hagané. 73, S959 (1987)
73) Hisatomi, R. et al.: CAMP-ISIJ. 5, 1249 (1992)
74) Steelmaking Committee, ISIJ: Private communication. March 1972
75) Steelmaking Committee, ISIJ: Private communication. March 1992
76) Steelmaking Committee, ISIJ: Private communication. June 1982
77) Shimada, Y. et al.: Tetsu-to-Hagané. 73, S993 (1987)
78) Komai, T. et al.: Tetsu-to-Hagané. 67, 1152 (1981)
79) Yanai, M. et al.: Tetsu-to-Hagané. 73, S281 (1987)
80) Okohira, K. et al.: CAMP-ISIJ. 1, 1161 (1988)
81) Steelmaking Committee, ISIJ: Private communication. November 1986
82) Miura, R. et al.: CAMP-ISIJ. 6, 1156 (1993)
83) Miura, R. et al.: CAMP-ISIJ. 4, 1320 (1991)
84) Steelmaking Committee, ISIJ: Private communication. March 1972
85) Yamamoto, K. et al.: Tetsu-to-Hagané. 67, S194 (1981)
86) Tanaka, H. et al.: CAMP-ISIJ. 4, 1319 (1991)
87) Tanaka, H. et al.: Tetsu-to-Hagané. 79, 1254 (1993)
88) Nagano, H. et al.: Tetsu-to-Hagané. 70, S145 (1984)
89) Masuo, N. et al.: Tetsu-to-Hagané. 73, S158 (1987)
90) Kuwatori, H. et al.: Tetsu-to-Hagané. 71, S900 (1985)
91) Tanaka, H. et al.: Tetsu-to-Hagané. 78, S761 (1992)
92) Okimori, M. et al.: CAMP-ISIJ. 3, 183 (1990)
93) Nishihara, R. et al.: CAMP-ISIJ. 3, 184 (1990)
94) Steelmaking Committee, ISIJ: Private communication. March 1990
95) Fukunaga, S. et al.: CAMP-ISIJ. 2, 260 (1989)
96) Imamura, A. et al.: CAMP-ISIJ. 1, 1258 (1988)
97) Imamura, A. et al.: CAMP-ISIJ. 1, 1259 (1988)
98) Imamura, A. et al.: Tetsu-to-Hagané. 78, 439 (1992)
99) Steelmaking Committee, ISIJ: Private communication. September 1987
100) Konishi, J. et al.: CAMP-ISIJ. 3, 260 (1990)
101) Tanaka, H. et al.: CAMP-ISIJ. 3, 252 (1990)
102) Sawada, I. et al.: CAMP-ISIJ. 3, 1090 (1990)
103) Kurata, K. et al.: CAMP-ISIJ. 1, 1284 (1988)
104) Tanaka, S. et al.: CAMP-ISIJ. 6, 1148 (1993)
105) Kuwatori, H. et al.: CAMP-ISIJ. 3, 1215 (1990)
106) Shimada, Y. et al.: Tetsu-to-Hagané. 73, S255 (1987)
107) Kitagawa, I. et al.: CAMP-ISIJ. 4, 261 (1991)
108) Steelmaking Committee, ISIJ: Private communication. March 1991
109) Hazama, S. et al.: Tetsu-to-Hagané. 66, S185 (1980)
110) Inada, T. et al.: CAMP-ISIJ. 7, 333 (1994)
111) Sato, N. et al.: Tetsu-to-Hagané. 66, S144 (1980)
112) Tanaka, H. et al.: CAMP-ISIJ. 3, 253 (1990)
113) Tanaka, H. et al.: Tetsu-to-Hagané. 78, 1464 (1992)
114) Steelmaking Committee, ISIJ: Private communication. July 1981
115) Hamaguchi, C. et al.: CAMP-ISIJ. 3, 1173 (1990)
116) Steelmaking Committee, ISIJ: Private communication. February 1990
117) Kitamura, S. et al.: Tetsu-to-Hagané. 68, S217 (1982)
118) Furuno, Y. et al.: Tetsu-to-Hagané. 68, S1009 (1982)
119) Tetsu-to-Hagané. 81, 409 (1995)
120) Osawa, M. et al.: Tetsu-to-Hagané. 74, 949 (1988)
121) Tezuka, M. et al.: Tetsu-to-Hagané. 59, S85 (1973)
122) Kohtani, T. et al.: Tetsu-to-Hagané. 61, S60 (1975)
123) Steelmaking Committee, ISIJ: Private communication. November 1974
124) Steelmaking Committee, ISIJ: Private communication. September 1991
125) Kudo, K. et al.: Tetsu-to-Hagané. 66, S855 (1980)
126) Kusano, A. et al.: Tetsu-to-Hagané. 69, S236 (1983)
127) Steelmaking Committee, ISIJ: Private communication. November 1973
128) Nakamori, Y. et al.: Tetsu-to-Hagané. 67, S903 (1981)
129) Kimura, H. et al.: Tetsu-to-Hagané. 67, S281 (1981)
130) Uchino, T. et al.: Tetsu-to-Hagané. 73, S925 (1987)
131) Okimori, M. et al.: Tetsu-to-Hagané. 81, T43 (1995)
132) Steelmaking Committee, ISIJ: Private communication. March 1984
133) Hirakawa, N. et al.: Tetsu-to-Hagané. 67, S137 (1981)
134) Kudo, K. et al.: Tetsu-to-Hagané. 66, S846 (1980)
135) Moritama, N. et al.: Tetsu-to-Hagané. 74, 1227 (1988)
136) Okimori, M. et al.: CAMP-ISIJ. 1, 276 (1988)
137) Okimori, M. et al.: Seitetsu Kenkyu. (334), 1 (1989)
138) Ikezaki, E. et al.: Seitetsu Kenkyu. (338), 35 (1990)
139) Okumura, H. et al.: CAMP-ISIJ. 1, 1241 (1988)
140) Hiramoto, Y. et al.: CAMP-ISIJ. 3, 1134 (1990)
141) Kido, S. et al.: CAMP-ISIJ. 2, 266 (1989)
142) Okimori, M. et al.: CAMP-ISIJ. 4, 304 (1991)
143) Imai, T. et al.: CAMP-ISIJ. 1, 1240 (1988)
144) Takigawa, I. et al.: CAMP-ISIJ. 2, 267 (1989)
145) Steelmaking Committee, ISIJ: Private communication. March 1989
146) Imai, T. et al.: CAMP-ISIJ. 1, 1242 (1988)

147) Okimori, M. et al.: CAMP-ISIJ. 1, 179 (1988)
148) Hisatomi, R. et al.: CAMP-ISIJ. 2, 1213 (1989)
149) Okimori, M. et al.: Proceedings of the 6th International Iron & Steel Congress. 1990, p. 401
150) Kajiwara, T. et al.: Tetsu-to-Hagané. 60, S457 (1974)
151) Steelmaking Committee, ISIJ: Private communication. March 1974
152) Maede, H. et al.: Tetsu-to-Hagané. 69, A181 (1983)
153) Steelmaking Committee, ISIJ: Private communication. March 1981
154) Kanemaru, K. et al.: Tetsu-to-Hagané. 67, S205 (1981)
155) Koga, N. et al.: Tetsu-to-Hagané. 67, S206 (1981)
156) Kusano, A. et al.: Tetsu-to-Hagané. 71, S211 (1985)
157) Nishihara, R. et al.: CAMP-ISIJ. 1, 206 (1988)
158) Nishihara, R. et al.: CAMP-ISIJ. 1, 1224 (1988)
159) Okamoto, K. et al.: CAMP-ISIJ. 3, 1174 (1990)
160) Okamoto, K. et al.: CAMP-ISIJ. 4, 302 (1991)
161) Okimori, M. et al.: Tetsu-to-Hagané. 80, T120 (1994)
162) Steelmaking Committee, ISIJ: Private communication. September 1989
163) Miyamura, K. et al.: Tetsu-to-Hagané. 60, S61 (1974)
164) Kudo, K. et al.: Tetsu-to-Hagané. 71, S197 (1985)
165) Steelmaking Committee, ISIJ: Private communication. November 1984
166) Kitamura, S. et al.: Tetsu-to-Hagané. 68, S868 (1982)
167) Noda, N. et al.: Tetsu-to-Hagané. 67, S900 (1981)
168) Kitamura, S. et al.: Tetsu-to-Hagané. 69, S264 (1983)
169) Steelmaking Committee, ISIJ: Private communication. November 1981
170) Okimori, M. et al.: Tetsu-to-Hagané. 80, T25 (1994)
171) Terada, T. et al.: Tetsu-to-Hagané. 66, S737 (1980)
172) Kitamura, S. et al.: CAMP-ISIJ. 3, 1228 (1990)
173) Steelmaking Committee, ISIJ: Private communication. September 1980
174) Tanaka, K. et al.: CAMP-ISIJ. 6, 1177 (1993)
175) Matsuzaki, K. et al.: Tetsu-to-Hagané. 73, S976 (1987)
176) Steelmaking Committee, ISIJ: Private communication. December 1982
177) Koga, N. et al.: Tetsu-to-Hagané. 71, S264 (1985)
178) Hisatomi, R. et al.: CAMP-ISIJ. 6, 1122 (1993)
179) Tanaka, H. et al.: CAMP-ISIJ. 6, 1123 (1993)
180) Tanaka, H. et al.: CAMP-ISIJ. 6, 1124 (1993)
181) Kusano, A. et al.: Tetsu-to-Hagané. 73, S286 (1987)