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Recent Trends and Future Prospects of Continuous Casting Technology

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Abstract:

The 1970s saw the establishment of basic equipment and operating technologies for the continuous casting process, and Japan's continuous casting ratio jumped from 6% to 60% in a mere 10 years. Since the 1980s, measures have been taken to improve the quality of continuously cast steel to meet the increasing severity of steel quality requirements. The same period has witnessed remarkable progress in productivity increase and labor savings, and the continuous casting ratio has exceeded 95% nationally. The corresponding figure for Nippon Steel is nearly 100% except for ultra-heavy plates and shapes This paper provides an overview of the advances made in continuous casting technology since its introduction to Japan. Descriptions here refer to tundish steel heating, mold steel flow control, soft reduction, and direct rolling as technologies that have rapidly advanced and spread in the past decade. Lastly, further improvement in productivity and the near net shape continuous casting (NNSCC) process are discussed as future tasks to be addressed to meet the rapidly changing social and economic environments.

1. Introduction

The principle of the continuous casting process originates in the test continuous caster of H. Bessemer of Britain in 1847. The 1947 test continuous casting machine of Junghans of former West Germany was the first application of the process to steel. His series of inventions comprised key technologies of today's continuous casting process, such as the open-ended water-cooled mold, mold oscillation, mold lubrication, and submerged nozzle.

Work on the development of test machines was continued in Europe, Germany and Austria, in particular. In Japan, Sumitomo Metal Industries participated in the Concast group and installed Japan's first continuous caster in 1955. During the decade that followed, the continuous casting process did not surpass the traditional ingot casting-primary rolling route in terms of productivity and economy and therefore its spread was not rapid. From the 1970s onward, however, the process has been extensively adopted with the support of various key technologies developed, as shown in **Fig. 1**.

The continuous casting process is much more advantageous than the conventional ingot casting-primary rolling route in terms of productivity, yield, energy and labor efficiency, and quality assurance, as shown in **Table 1**. For this reason, it rapidly spread over the world including Japan where, in particular, it proved an effective means of filling the steel demand in the high-economic growth period and overcoming the two successive oil crises.

The history of the continuous casting process in Japan may be reviewed in four periods, each lasting about ten years.

First period (1960s) - Establishment of industrial continuous casting process

*1 Kimitsu Works

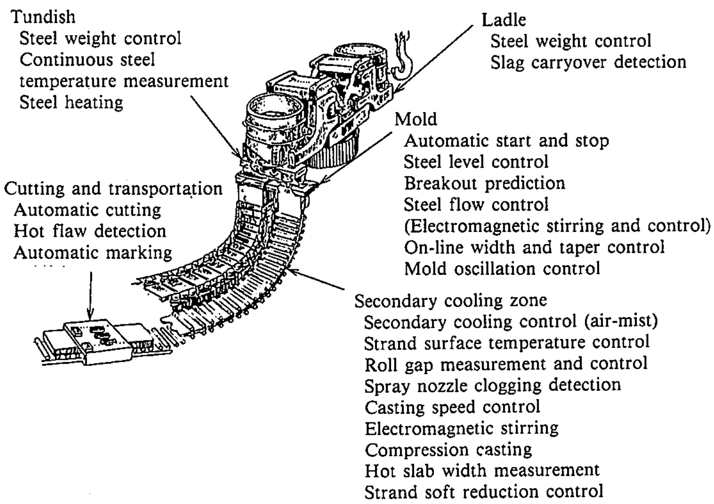

Fig. 1 Key technologies supporting continuous casting process

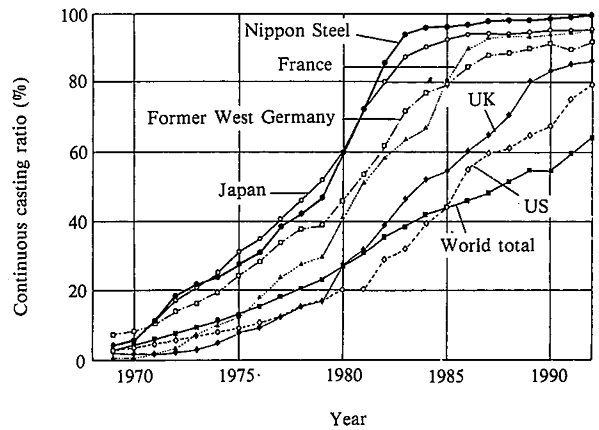

Fig. 2 Change in continuous casting ratio

Table 1 Comparison of continuous casting process and ingot casting-primary rolling process

	Continuous casting process	Ingot casting-primary rolling process
1. Productivity (molten steel to slab)	30 to 60 min	1 to 2 days
2. Yield (molten steel to slab)	96 to 99%	80 to 90%
3. Energy saving	1/2 to 1/4	Base
4. Labor saving	6 to 10 persons/shift	20 to 30 persons/shift
5. Plant floor space saving	1/3 or less	Base
6. Miscellaneous	Steel quality and the homogeneity of quality are better than achievable by ingot casting-primary rolling process, and heavy work load is greatly alleviated	

- The continuous casting process was commercialized mainly in billet and bloom casting, through which basic technologies of the process were accumulated.

  Second period (1970s) - Size growth and technological development (see **Fig. 2**)
- Slab casters were successively introduced, and applicable steel grades drastically increased. The continuous casting ratio grew from 5.6% in 1970 to 52% in 1979. Nippon Steel's Oita Works built as a dedicated continuous casting works symbolizes this growth period.

  Third period (1980s) - Maturity (see **Fig. 2**)
- Technologies were established for continuously casting high-grade steels, and the range of process application expanded to cover almost all steel grades. The continuous casting ratio reached 95% in the late 1980s.

  Fourth period (1990s) - Appearance of new continuous casting processes
- Thin-slab casting, strip casting, and other new continuous casting processes were developed in succession to lessen or completely eliminate the role of the hot rolling process. Nucor of the United States and Arvedi of Italy started the commercial production of hot coils by the thin-slab casting process.

2. Technological Background of Development in Continuous Casting Process

In the following, technological background for the development of continuous casting process is reviewed from the point of view of productivity, energy consumption, range of applicable steel grades, and quality assurance.

2.1 High productivity

The continuous casting process was adopted first for electric arc furnace carbon steel. The reasons were that the productivity of the continuous casting process matched that of the electric arc furnace process and that the continuous casting process brought about large gains in production yield and quality.

In the 1970s, the continuous casting process suddenly found widespread use for converter steels. This was made possible by various key technologies, such as sequence casting, high-speed casting, technology for shortening cast preparation time and shutdown time, refractories technology for prolonging submerged nozzle life, changeable width mold and casting dissimilar steel grades.

2.2 Energy conservation

The 1973 and 1978 oil crises had decisive effects on the development of continuous casting technology in Japan. The first oil crisis fell on the initial development period when the continuous casting ratio was 20%. Against the background of strong social demand for energy conservation, the continuous casting process was considered the most energy-efficient process and was applied to an increasing number of steel grades. This energy-saving drive also expedited the development of technology to improve the slab surface quality for hot charge rolling (HCR) whereby as-cast hot slabs are charged directly into the reheating furnace of the hot rolling mill.

The continuous casting ratio was 50% when the second oil crisis broke out. The hot direct rolling (HDR) process, an advanced version of HCR, was developed and implemented at Nippon Steel's Sakai Works to register energy savings of unparalleled magnitude in the world.

The progress of the HCR and HDR processes owed much to the development of high-temperature defect-free slab manufacturing technology, including scientific elucidation of factors responsible for slab surface defects, improvement in mold powder, mold level control, compression casting, short-pitch divided rolls, air-water mist cooling, and slab insulating and heating.

2.3 Expansion of the range of applicable steel grades

The 1970s saw a remarkable increase in the continuous casting ratio. Continuous casting was initially applied to killed steel for plates. As more steel grades came to be continuously cast, rimmed steel for sheet products still remained to be continuously cast. It deserves special mention that the continuous casting process was applied for the first time to silicon-manganese-killed steel as a pseudo-rimmed steel for cold-rolled products, and this gave an impetus to the continued advancement of the process. Continuous casting of aluminum-killed steel by the aid of argon injection into the mold was tried in the last half of this period. The continuous casting process grew to cover such high-grade sheet products as pre-coated steel sheets.

In the 1980s, efforts were focused on the continuous casting of remaining high-grade steels. A typical example was steel plates for nuclear pressure vessels, cryogenic applications, and service in acid environments. These steels were successfully brought within the application range of continuous casting thanks to innovation in refining and soft reduction technologies. In the sheet steel category, weakly deoxidized steel for shadow masks and porcelain enameling sheets came to be continuously cast through the introduction of in-mold electromagnetic stirring. As for long products, wire rods for automobile springs and welding rods became continuously castable through such innovative developments as oxidation-free casting with a shielded tundish, tundish steel heating, and in-mold electromagnetic stirring.

2.4 Quality improvement

The 1970s and 1980s also witnessed steel quality enhancement. Mass production steels had to meet ever increasing severity of quality requirements and service environments. Any higher continuous casting ratio no longer could be expected without drastically improving the cast steel quality.

Of the technologies developed during this period, molten steel treating technology made remarkable progress. Nonmetallic inclusions were countered by preventing the carryover of ladle slag, using advanced refractories, shrouding the tundish, installing weirs and dams in the tundish, heating molten steel in the tundish, and applying electromagnetic force to molten steel in the mold. Slab surface cracks were coped with by optimizing mold cooling, using improved mold powders, and controlling the strand surface temperature in the secondary cooling zone. Against center segregation, electromagnetic stirring and low-temperature casting were adopted at first, and lately soft reduction came to be applied to high-grade steels.

The same period also saw the introduction of a vertical bending (liquid-core bending) machine profile on sheet slab casters to promote the flotation of inclusions and bubbles.

3. Changes in Continuous Casting Machine Profiles

Various continuous caster profiles are shown in **Fig. 3**.

From the 1950 to 1960s when the continuous casting process was commercialized, many continuous casters of the structurally simple vertical type were built. The vertical type, however, was disadvantageous in that the machine height had to be greatly increased to enhance productivity and that the ferrostatic pressure of molten steel increases so much as to make it difficult to restrain strand bulging.

Bow-type machines came to be developed in or around 1963 with the aim of raising productivity and reducing the equipment size, and as a result in the middle 1960s, casters of this type started commercial production in Europe. In Japan, construction of bow-type machines was commenced in the 1960s, and those casters built one after another during the period from 1970 to 1980 are mostly of the bow type for both blooms and slabs.

After the bow type, a vertical-bending type came into spotlight in or around 1980. The vertical-bending type referred to here is such that the strand is first run straight over 2 to 3 m from the mold level and is then bent while its core portion is still unsolidified.

This type combines in itself the merits of both the vertical and bow types, namely, the former's high efficiency of inclusion and bubble removal by flotation and the latter's high productivity. For these advantages, the vertical-bending continuous caster has become an indispensable unit of equipment for manufacturing high-grade sheet products for use in automotive and beverage can steel sheets that call for very high steel cleanliness.

With the advent of the 1980s, machines to cast steel in the horizontal direction were introduced for billets and blooms, mainly by electric arc furnace steelmakers in Europe and the United States. Japan started the development and introduction of horizontal continuous casters about the same time. Large horizontal casting machines were started up at NKK's Keihin Works in 1983 and at Nippon Steel's Hikari Works (see **Fig. 4**) in 1989.

As implied by its name, the horizontal continuous caster has a tundish, mold, withdrawal rolls, and all other components arranged horizontally. The plant building height can be reduced

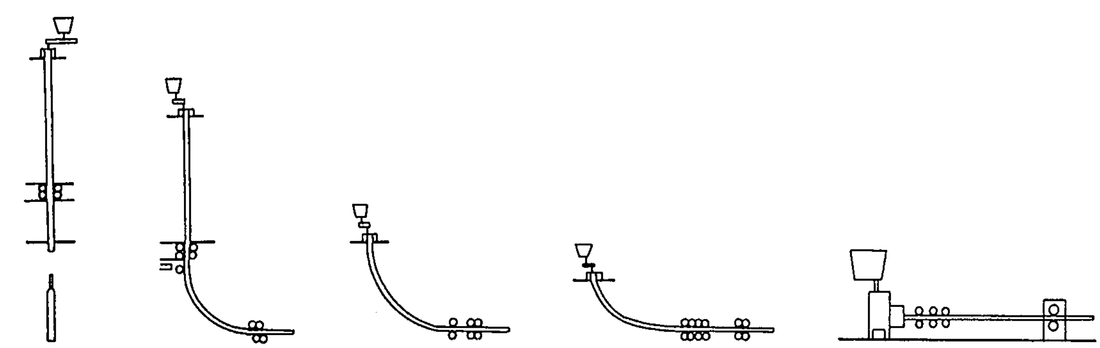

Fig. 3 Continuous casting machine profiles

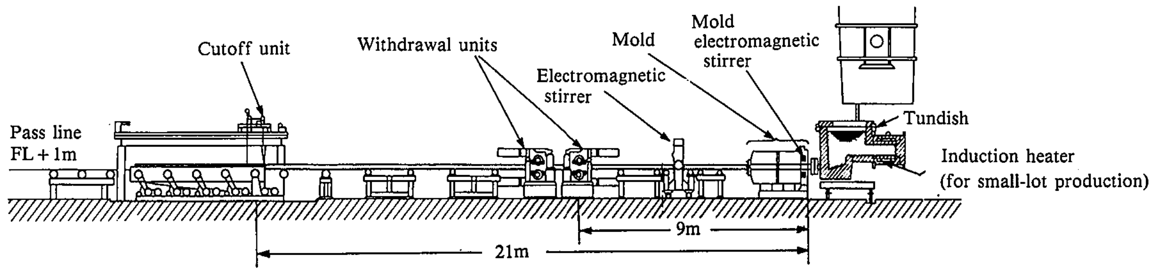

Fig. 4 Horizontal continuous caster at Hikari Works

to one-third to one-half from the vertical design. The ferrostatic pressure of molten steel is thus sharply reduced to drastically simplify the equipment configuration and slash the construction cost by about two-thirds. The mold is linked direct to the tundish, so that powderless casting can be done. The horizontal continuous caster requires no spray cooling because the ferrostatic pressure is extremely low, nor does it require strand bending and unbending, which is the case with the bow and vertical-bending continuous casters. This is a great advantage of this type in terms of cast steel quality.

The largest problem with the equipment and operating technology of the horizontal continuous caster is how to secure sound initial solidification with the ceramic break ring installed on the upstream side of the mold. Hikari Works controlled the casting cycle of pull, pause, and push to an optimum pattern with accuracy of ±0.1 mm with the aid of an AC servomotor, backlashless speed reducer, and high-speed microprocessor. Defects peculiar to the horizontal continuous caster such as cold shut, cracks, and hot tears were thereby solved to produce stainless steel castings of good quality.

4. Recent Technological Trends

Continuous casting progressed through the 1980s toward technological maturity, and in the meentime gave birth to some new continuous casting processes. **Table 2** lists those continuous casting technologies developed or brought to perfection during the decade onward .

Here are reviewed some of those technologies, namely, molten steel heating in the tundish, flow control in the mold, and which have made particularly remarkable progress in the past decade.

4.1 Molten steel heating in tundish

In continuous casting, the molten steel temperature is an extremely important control factor from the point of view of both quality and operation. Ideally, the molten steel temperature should be always controlled within certain limits. The molten steel temperature in the tundish in actual casting varies by 15 to 25°C from ladle to ladle owing to temperature fluctuations in the refining process and temperature drop during casting (particularly at such unsteady-state portions as the start of a cast, ladle change during sequence casting, and end of a cast).

If molten steel heating technology is applied to such temperature-drop portions, the temperature variation can be held within 5 to 10° throughout the cast, and quality deterioration due to the temperature drop of unsteady-state strand portions, and such operation troubles as submerged nozzle clogging can be drastically reduced (see **Fig. 5**).

The molten steel in the tundish is heated by the induction heating method or plasma heating method. Nippon Steel has applied the induction heating method at Yawata and Muroran and the plasma heating method (see **Fig. 6**) at Hirohata and Nagoya. These tundish steel heating technologies will probably be employed more extensively in the near future (for details, refer to the article "Innovative Technologies in Continuous Casting Tundish" in this issue).

4.2 Flow control in mold

The molten steel flow in the mold is controlled by stirring or braking the molten steel with electromagnetic force generated by the coils installed behind the water-cooled copper plates of the mold.

The idea of mold steel flow control started with the technolo-

Table 2 Main continuous casting technologies from 1980s onward

	Key word	Technology
Tundish	Ladle slag Secondary oxidation Steel temperature control Refractory cost	Ladle slag carryover detection unit Completely shielded tundish Induction heating, plasma heating Recycle of tundish in hot condition
Mold	Coating Mold cooling Mold oscillation Steel flow control Breakout	Coating technology (special material, multilayer coating) Uniform cooling slits High-cycle, non-sine-curve waveform Electromagnetic stirring and control Breakout prediction system by neuro-computer
Secondary cooling zone	Uniform cooling High-temperature slab delivery High-speed casting Center segregation	Air-Mist spray cooling, spray nozzle clogging detection No spray cooling of strand edges, liquid-core reheating, roll cooling Compression casting (CPC), divided roll Strand reduction (soft or heavy reduction)

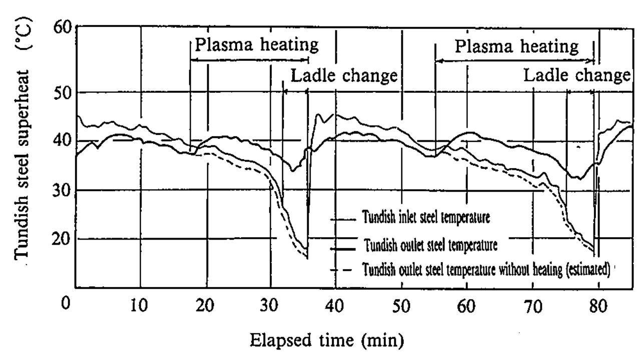

Fig. 5 Effect of tundish steel heating

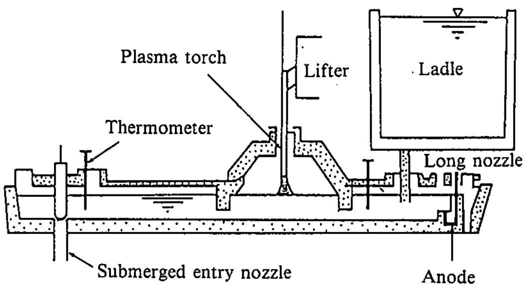

Fig. 6 Tundish steel heating (plasma heating) at Nippon Steel's Hirohata Works

gy developed at Nippon Steel's Hirohata Works for stirring the molten steel in the mold of a slab caster to ensure the soundness of the initially solidifying shell. Stirring the molten steel in the mold reduces subsurface inclusions and bubbles, equalizes the thickness of the initially solidifying shell, and decreses surface segregation. Longitudinal cracks and other surface cracks can be sharply reduced as a result. In-mold electromagnetic stirring made it possible to continuously cast some weakly deoxidized steels which had been considered difficult in the past. Applied also to blooms, the in-mold electromagnetic stirring technology proved greatly effective in improving the surface quality, and macrosegregation of blooms. At Nippon Steel, this technology is now applied to slab casters at Hirohata and Oita and to bloom casters at Muroran, Kimitsu and Hikari.

A high casting speed of 2.0 m/min and above is aimed at to raise productivity, resulting in a significant increase in the flow velocity of molten steel in the mold. The principal consideration for operation stability and quality assurance during high-speed casting is the optimum control of the flow state of molten steel in the mold.

As the casting speed increases, the amount of molten steel entering the mold per unit time naturally increases. Any slight disturbance in the flow of the molten steel disturbs the formation of the solidifying shell in the mold, retards the flotation of inclusions, and leads to such troubles as mold powder entrainment into the strand.

In countering these problems, various methods are under study for stabilizing the molten steel flow in the mold by braking the molten steel stream through the submerged nozzle into the mold (stationary magnetic field, mobile magnetic field, localized magnetic field, level magnetic field, etc.). (For details, refer to the article "Advances of Applied MHD Technology for Continuous Casting Process" in this issue.)

4.3 Soft reduction

Soft strand reduction was developed and implemented in the 1980s as technology to improve center segregation and porosity. Traditionally, low-temperature casting and electromagnetic stirring were employed as key technologies to improve center segregation in both slabs and blooms, and this proved effective against macrosegregation. As quality requirements gained stringency, however, semimacrosegregation and microporosity, which had been traditionally considered harmless, became important factors in the control of product properties.

This problem was solved by soft reduction technology in slab casting. The strand is gradually compressed to compensate for the amount of its solidification shrinkage. This soft reduction inhibits the flow of molten steel accompanying the solidification shrinkage and improves microsegregation, let alone semimacrosegregation and microporosity.

In bloom casting, the soft reduction process started to be extensively applied to prevent center segregation and microporosity in high-grade bar and rod steels in the late 1980s. Since blooms have narrower final liquid cores than slabs, they can be effectively compressed by crown rolls or disk rolls with high reduction efficiency. Rolls optimized in geometry for specific bloom sizes are used at Yawata, Muroran, and Kimitsu.

4.4 Manufacture of high-temperature cast steel sections

Technology of manufacturing high-temperature defect-free cast steel sections is a minimum necessary condition for the HDR process as noted previously. To reduce energy consumption, to rationalize production, and to shorten the production time by eliminating some process steps, it is important that matching between the converter steelmaking and continuous casting steps and matching between the continuous casting and hot rolling steps should be accurately performed on a minute basis. Qualitywise, the HDR process rolls the cast steel without reheating, and thus the scale loss is reduced to a half. This makes it important to minimize subsurface defects. This requirement was met with an overall improvement measure combining: optimization of secondary refining to enhance the steel cleanliness, prevention of air oxidation between the tundish and mold, improvement of mold level control accuracy, and improvement of mold powder properties.

These technology developments resulted in establishing a practical system for producing high-temperature and defect-free slabs and realizing the directly linked continuous casting-hot direct rolling process (CC-HDR). The CC-HDR process started up at Nippon Steel's Sakai Works in 1981, NKK's Fukuyama Works in 1985, and Nippon Steel's Yawata Works in 1987.

As for the bar and wire rod series, hot charge rolling (HCR) technology is already established by which as-cast blooms are hot rolled into billets. Some steelworks are even rolling bars and rods from as-cast billets for greater energy savings and higher production yield. In this connection, Nippon Steel started up the CC-HDR process for billets at Muroran in 1991, and have solved practically all the quality problems involved to date.

Billets being small in section size, are bound to be cast at high speed. The high-speed casting makes it difficult to control inclusions and segregation in as-cast billets. The change of billet-making process from rolling to casting tends to reveal the latent microcracks hitherto considered harmless and the surface defects removed as scale loss in the rolling process. Active development and testing efforts are expended to improve mold powder properties, raise the mold level control accuracy, and apply steel flow control, all aimed at securing sound initial solidification.

5. Future Prospects

As discussed above, the slab and bloom casting technologies that have made remarkable progress in the past are now in the maturing stage. Worth noting here is the importance of guarding against the obsolescence of equipment and technology through incessant innovation.

In the realm of continuous casting, conventional types of casters will gain in casting speed, and be further automated and mechanized for still higher productivity. A major challenge for the next generation will be the near net shape continuous casting

(NNSCC) process aimed at lessening the overall mill load.

5.1 Increase in casting speed of existing continuous casters

Japan's slab casters built in the 1970s are approaching replacement because of obsolescence, and their replacement or major modification plans are being implemented. Nippon Steel's principal continuous casters also have been converted to the vertical-bending type and have had their control systems renewed in the past several years. These renewed or modified machines incorporate the technologies listed in **Table 2**, and feature drastic increases in productivity.

Large slab casters built in the 1970s have casting speeds of 1.2 to 1.8 m/min and monthly casting capacities of about 200,000 tons by two strands. With better mold powder, improved mold oscillation, optimized machine profiles (multipoint bending and straightening and vertical-bending), and refined mold steel flow control, the latest casters under planning are designed for a casting speed of 2.5 m/min or higher and casting capacity in excess of 300,000 tons/month/2 strands.

5.2 Automation and mechanization

As for automation and mechanization in continuous casting, technologies of detecting ladle slag carryover, continuously measuring steel temperature, controlling steel weight, and recycling hot tundishes have been commercialized for the ladle and tundish. Technologies of automatically starting and stopping casts, automatically feeding casting powder, and predicting breakouts have been put to practice for the mold. For the secondary cooling zone and downstream, subdivided control of secondary cooling and roll gap to accommodate tandem casting, automatic cut length determination, and unattended cutting with cutoff torches of improved reliability have been accomplished.

Now that elementary technologies have been established for respective areas of the continuous casting process, recent caster renewal and modification plans for two-strand running are designed for a crew strength of only 4 to 5 operators per shift compared with the former 6 to 8 operators per shift. Automation and mechanization will proceed further with the increase of equipment reliability and through such measures as the introduction of artificial intelligence into process computer systems.

5.3 Toward commercialization of NNSCC process

The NNSCC process has advanced for bloom sections, such as beam blanks and hollow billets, and has already been in commercial operation at some plants. Thin-slab casters to cast 40 to 60 mm thick slabs to omit rough rolling in the hot rolling process have just started up, mainly at electric arc furnace steelmakers in the United States and Europe.

Strip casting test facilities of about 10 tons in capacity were built in succession in the 1980s, and key technologies have been practically established for strip casting. Nippon Steel's Hikari Works has conducted casting tests of a 1.2-m wide stainless steel strip and ascertained the feasibility of its commercialization in terms of both quality and economy.

These novel continuous casting processes still have many technological problems to solve to be competitive against the conventional casting processes, such as inclusions, solidification structure casting geometry and other quality-related problems, as well as problems associated with productivity and production capacity. For all these problems, however, they are viable and are destined to grow as casting technologies of the next century.