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# Development of Continuous Casting Technologies at Kawasaki Steel

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## 1 Introduction

By 1985, the ratio of continuous casting in Japan had reached 91.4%. Although the two oil crises of 1973 and 1979 had reconfirmed the advantages of continuous casting as an energy-saving process which allows the user to simplify production processes, and thus had established the position of continuous casting in the steelmaking process. 1985 was an historical turning point when the yen began to appreciate dramatically and the environment in which the steel industry operates today revealed itself for the first time. Moreover, in 1985, the American auto industry, which had been in recession since the second oil crisis, once again achieved its earlier level of production. After 1985, Japan steel industiries had to be faced with an international competitiveness governed by exchange rates considerably.

Against this background, the continuous casting process was required to meet the following requirements:

(1) High-efficiency production
(2) Production of high-quality slabs
(3) Direct linkage with the subsequent process

This report summarizes the progress of continuous casting technology over the last ten years (1985–95) from the viewpoint of both operation and product quality.

## 2 Techniques for Improving Productivity

### 2.1 Techniques for Improving the Working Ratio

Various techniques have been developed to increase casting speed, reduce non-operating time, and improve the working ratio (operating ratio) with the aim of increasing continuous casting capacity. At Mizushima Works No. 5 continuous casting machine (CCM), the technique of continuous-continuous casting of different grades of steel by introducing a coolant into the mold to create a solidified bulkhead in the strand was adopted as a standard practice in 1978, followed by automatic slab width changing during casting, which was adopted in 1979. Using these two techniques, the number of heats per dummy bar rose to approximately 25, and monthly production of 180 000 t was achieved.[1)] Subsequently, in 1984, the tundish capacity was increased from 45 t to 60 t to improve slab quality and raise productivity, and the world's first electromagnetic brake (EMBR) was introduced.[2)] However, with increased casting of materials having strict surface quality and internal quality requirements, as represented by ultra-low carbon (ULC) steel, it became difficult to achieve substantial improvements in productivity by increasing the casting speed.

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Efforts were therefore made to improve the operating ratio by casting super-long continuous sequences, and in 1991, a super-long sequence of 927 casts was achieved, establishing a record of 247 000 t of cast steel with one dummy bar.

The main techniques which made it possible to cast super-long sequences were prolongation of mold life, relaxation of the restrictions on the amount of width change by high-speed width expansion, and the tundish hot recycling to cope with small-lot orders.[3]

(1) Mold life prolongation

Because the majority of factors which affect the life of the mold have their origin in high copper-plate temperature, the shape and pitch of the cooling grooves was modified to obtain stable, adequate cooling performance. As a measure against wear of the lower part of the copper plates, NiFe (Fe: 8–10%) plating, which offers superior wear resistance, was adopted for practical use in combination with improvements in the range and thickness of the plating, and continuous use of one set of plates for 1 000 heats was achieved in 1989.

In 1994, the combined use of cooling in the subcool boiling region and thinner copper plates made it possible to reduce the surface temperature of the copper plates at the meniscus by 100°C in comparison with forced convection cooling,[4] and on-line mold life now exceeds 3 000 heats at Mizushima Works No. 4 CCM.

(2) High-speed mold width expansion

To increase the flexibility of continuous-continuous casting, high-speed mold width expansion was adopted in combination with a sizing press at the hot strip mill, eliminating the restrictions on the amount of mold width change. An original pattern which considers bulging strain was also developed for the rate of narrow-face movement. As a result, interruptions of the continuous-continuous casting sequence for width changes are no longer required.

(3) Tundish hot recycling

Preheating of the next tundish is sometimes inadequate when small-lot orders are being cast. To solve this problem, tundish recycling within a limited period of time was developed as a standard operating practice. In this technique, the remaining steel in the tundish is discharged to prevent interruption of continuous-continuous casting while the next tundish is preheated.

**Figure 1** shows the number of continuous-continuous casts per dummy bar and the trend in the operating ratio at Mizushima Works No. 5 CCM. The continuous-continuous number per dummy bar increased dramatically after 1989, and it became possible to maintain a stable operating ratio of 90%.

However, when highly synchronized operation with the hot rolling mill is required for operation of the steelmaking shop, the continuous-continuous casting of different steel grades to improve the working ratio can have a negative effect on direct hot charge rolling (DHCR), because the continuous casting of multiple heats requires a check of the chemical analysis of the steel at points where the heats are joined, and thus allows the temperature of the slabs in the machine to drop while the operation is stopped. The method of dummy bar top insertion was therefore adopted at No. 4 CCM, which began operation in 1993, shortening the preparation time for casting by 12 min from the 50 min required with dummy bar bottom insertion, and made it possible to achieve an operating ratio of over 90%, even with an average continuous-continuous casting number per dummy bar of 5 heats. Moreover, the adoption of a large-capacity 70 t tundish, straight mold, second-generation EMBR (Kawasaki Steel's FC Mold: Flow Control Mold), and small-diameter divided rolls enabled high-speed casting at a maximum 2.5 m/min, and a monthly record of 277 000 t was acheved in May 1995.

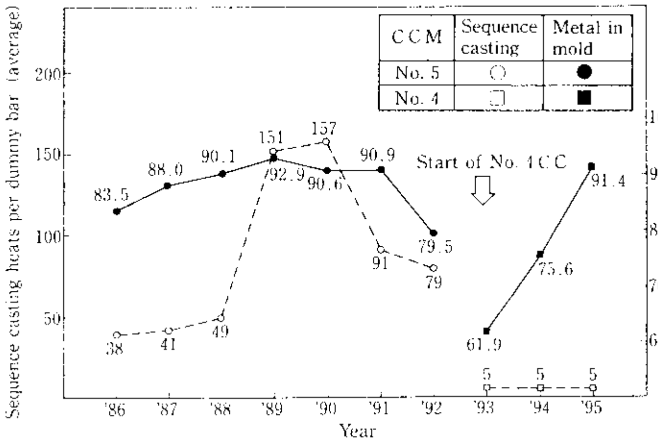

Fig. 1 Change of sequence casting and time ratio of metal in mold in No. 5 CCM and No. 4 CCM at Mizushima Works

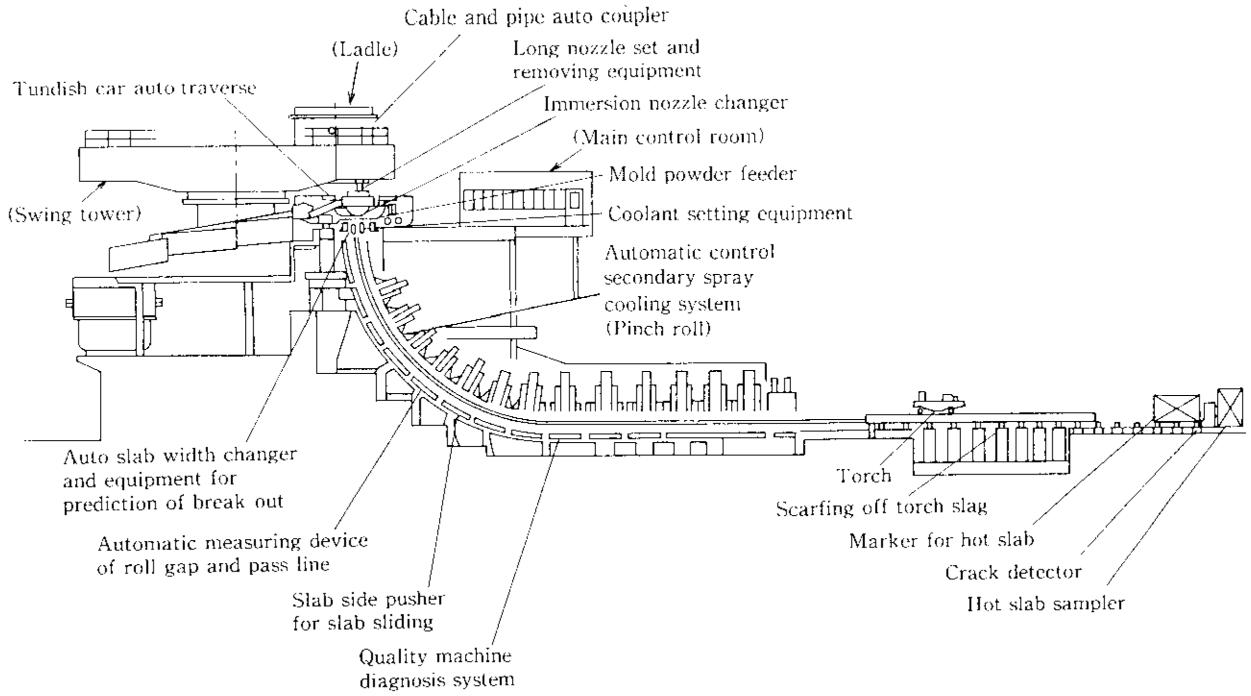

Fig. 2 Schmatic diagram of automated equipment in continuous casting process

## 2.2 Automation and Man-power Saving Techniques

Automation of the continuous casting operation began with main jobs such as mold width changing during casting, control of the amount and speed of casting, and cooling water control, followed by the study of the automation of skilled jobs which must be performed in a high-temperature environment. In 1987, a number of such jobs were automated, including connection of the power supply and utilities between the ladle and swing tower, immersion nozzle exchanges, setting of the connecting rods for continuous-continuous casting of different grades of steel, and sampling from hot slabs.[5] An outline of the automation of these tasks is shown in **Fig. 2**.

In 1989, tundish exchange, which requires the largest number of personnel, was automated to enable a single operator to perform centralized control of a entire series of tundish exchange jobs including transfer of the tundish car, setting of the immersion nozzle, and setting of the connecting rods for continuous-continuous casting of different grades of steel.[6]

The workinng environment was improved by introducing a brick demolition machine and automatic refractory gunning machine and strengthening the dust collectors, as shown in **Fig. 3**, and as a result, the time required for preparatory jobs was reduced by approximately 60%.[7]

In addition to these automation techniques, the first EIC integrated system was introduced at Mizushima Works No. 4 CCM to centralize the monitoring and operation of the continuous casting process and unify information.[8] Information on electrical, instrumentation, and computer equipment can now be viewed on the same screen, and the condition of unitary electrical and mechanical equipment can be monitored and controlled, contributing to labor savings in the operator position.

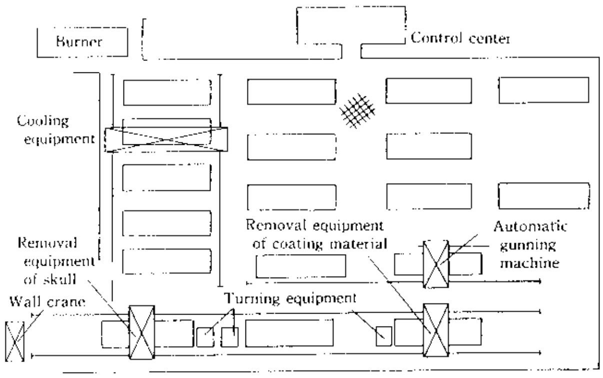

Fig. 3 Layout of the tundish service yard

Completely unmanned operation of the shipping line was realized, with centralized monitoring from the casting floor until slabs are loaded onto automatic slab transfer cars after torch cutting. An automatic sliding nozzle exchanger was installed on the casting floor to support the continuous hot recycling of tundishes and is used by operators in tundish preparation work; as a result, the frequency of off-line tundish preparation work is limited

Table 1 Key technologies for high productivity and high quality

| Equipment | Technologies of No. 4 C C at Mizushima Works |
|---|---|
| Tundish | Large tundish without air contamination |
| Mold | Adoption of Flow Control Mold<br>High accurate and reliable mold level control<br>High frequency oscillation system with hydraulic drive |
| Roller apron | Vertical zone below mold (3 m)<br>Mutipoints bending and unbending<br>Adequate secondary cooling pattern with mist spray cooling system<br>Short-pitch divided rolls for all the segments |

to two to three times per month, and the number of personnel engaged in tundish preparation has been reduced substantially.

### 2.3 Techniques for Continuation/ Synchronization of CCM and Rolling Mill Operation

Direct hot charge rolling of blooms was introduced at Mizushima Works in 1983, when No. 1 CCM and No. 3 CCM were linked to the rolling mill by automatic hot bloom transfer cars, and the DHCR ratio was eventually increased to 92.1%.[9] Although process linkage was limited to hot charging (HCR) at the slab caster due to equipment restrictions, slab DHCR began in 1993 following the construction of No. 4 CCM, which is linked to the hot rolling mill by automatic hot slab transfer cars (D-liners).

Production technology for high-temperature defect-free slabs and quality assurance techniques are indispensable for ensuring the effectiveness of DHCR. The techniques shown in **Table 1** were introduced to make high-quality, high-speed casting possible.

Because the distance from No. 4 CCM shop to the reheating furnace is 670 m, it is essential to minimize the slab temperature drop during transportation. Moreover, the structure of the insulated chamber of the D-liner was also designed to withstand frequent use at high temperature.[10] **Figure 4** shows a cross-sectional view of the D-liner. Long ceramic fibers with superior flexibility and strength was adopted as the refractory material of the upper door, a material with good resistance to high-temperature oxidation and thermal deformation was selected for the closing device, and material with low thermal transfer characteristics was chosen as the floor and wall refractory. This design makes it possible to hold the temperature drop during transport with the D-liner to 10°C or less, and to charge slabs into the reheating furnace at high temperatures of 850°C or over, as shown in **Fig. 5**.

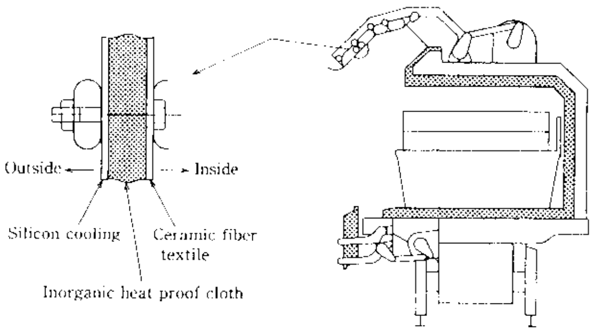

Fig. 4 Cross section of D-liner

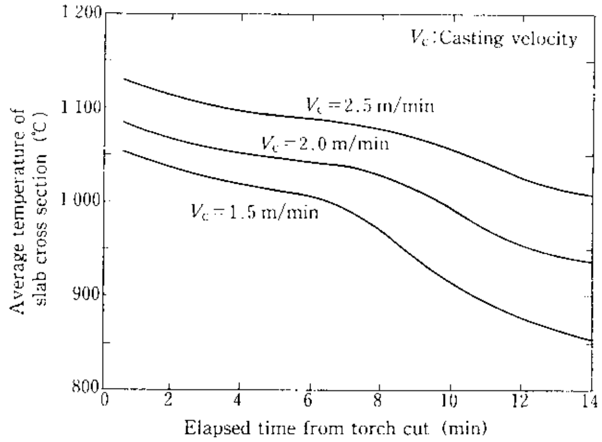

Fig. 5 Transition of slab temperature

## 3 Manufacturing Techniques for High-quality Slabs

Chiba Works No. 3 steelmaking shop uses Q-BOP converters, which are characterized by reduced oxygen content at a given turndown C value. To take advantage of this feature, a vertical bending type caster was constructed and put into operation in July 1981 at Chiba to produce high-quality slabs as meterial for cold-rolled sheet. By 1985, the continuous casting ratio had effectively reached saturation in plate, bar, stainless, and specialty steel production, and efforts over the most recent ten years have therefore focused on the continuous casting of slabs for sheet. During this same period, the ratio of coated steel sheets also increased significantly, and stricter requirements for the surface quality of coils were a feature of the period.

### 3.1 Advanced Technology for Control of Initial Solidification: FC Mold

The continuous annealing line (CAL) rapidly replaced the batch process in the production of steel sheets. The technology which made this possible was a development of decarburization treatment at RH degasser, which makes it possible to reduce the carbon content of steel in

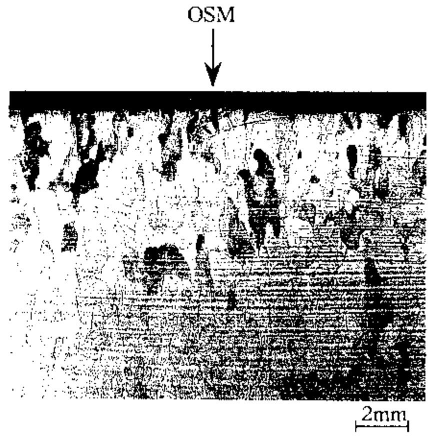

Photo 1 Blow hole trapped at inside of the oscillation mark (OSM) hook

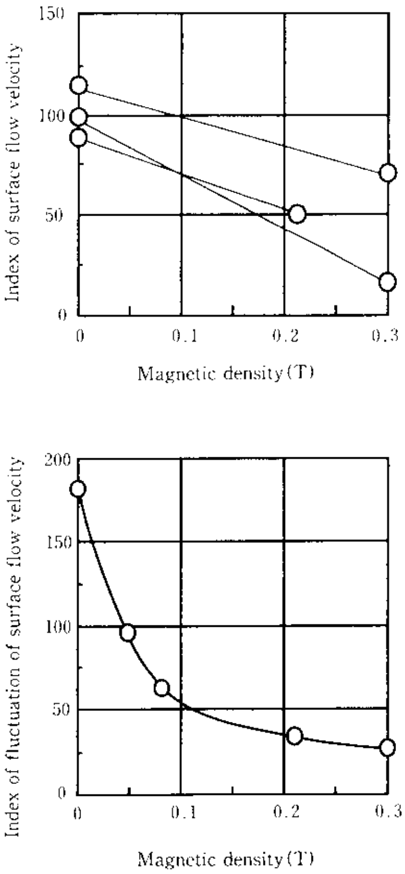

Fig. 7 Effect of magnetic density on surface flow velocity and its fluctuation of molten steel in the mold

products to under 20 ppm, and has now progressed to the point where requirements under 10 ppm can also be satisfied. However, it is known that ultra-low carbon (ULC) steel products are more susceptible than low carbon steel to surface defects. Early stage solidification in the mold is sensitive to carbon content because gas bubbles and non-metallic inclusions are easily trapped in deep oscillation marks, as shown in **Photo 1**.[11,12] For this reason, a more advanced technique for controlling early stage solidification, which would be capable of obtaining sound slabs, became necessary.

The Flow Control Mold (FC Mold) meets this requirement. The initial configuration of the EMBR, as mentioned in Chapter 2, was characterized by a static magnetic field in the mold,[13] but this function was pursued to its limits in the FC Mold. Structurally, uniform and un-interrupted magnetic fields are arranged uniformly acrooss the wide face of the mold in upper and lower steps,[14] as shown in **Fig. 6**. Applying the magnetic fields controls the flow of molten steel in the mold, which increases the temperature of the steel at the meniscus by 5–10°C.[15] A decrease in the average surface velocity at the meniscus and a marked reduction in flow rate variations can also be observed (**Fig. 7**).

These features have made it possible to reduce the incidence of product surface defects attributable to mold-powder remarkably, even when casting ULC at high speeds of 2 m/min or more, because mold powder entrapment by vortexes in the meniscus and by excessive steel flow velocity have been completely eliminated. In

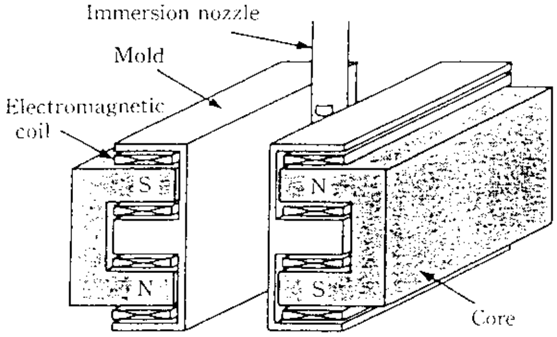

Fig. 6 Flow control mold (FC Mold)

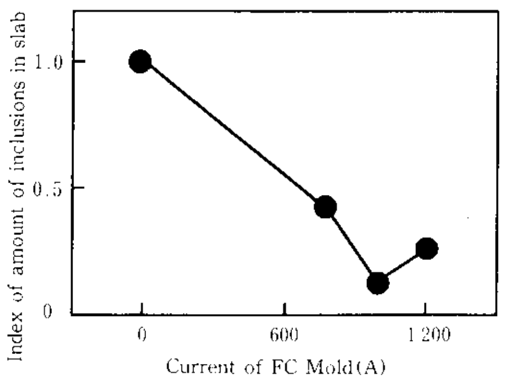

Fig. 8 Effect of FC Mold on cleanness of slab

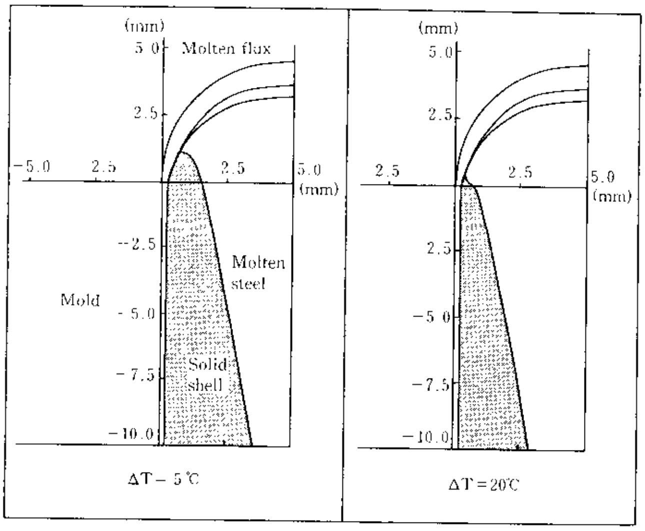

Fig. 9 Influence of super heat of steel on the initial solidification

addition, because the static magnetic field at the bottom side reduces the penetration depth of the molten steel stream, the internal cleanliness of slabs has also improved (**Fig. 8**).[15)]

Because the conventional continuous casting process today is based on the meniscus solidification of a free surface, the initial solidification behavior in the vicinity of the bath surface and mold surface is extremely important for obtaining a sound product surface and will continue to be an important topic of research and development. For example, numerical calculations by one of the authors indicate that the condition of the initially solidified shell varies greatly depending on the degree of superheat (**Fig. 9**). Thus, since initial solidfication are to be considered in combination with molten steel flow, various problems await further work, with the FC Mold is one possible avenue of development.

### 3.2 Advanced Technology for Control of Final Solidification: Continuous Forging Process for Blooms

Inverse V segregation is an inherent drawback of the production process with bottom-poured ingots. Simiarly, centerline segregation is inherent to the continuous casting process, and much effort has been devoted to educing it. In bloom casting, final solidification unavoidably occurs in a small area, which tends to deterioate the concentration of segregation components. With high carbon products such as bearing steel, steel for piano wire, and steel for tire cord, in addition to the fact hat there is a large absolute amount of solute, the proessing of products frequently involves heat treatment, nd defects have tended to occur due to changes in the hardness of the martensite structure. A continuous forgng technology for blooms was therefore developed as a undamental solution to the problem of centerline segreation.

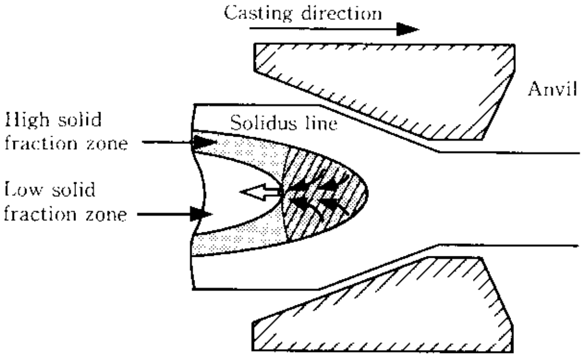

Fig. 10 Concept of continuous forging process

In the continuous forging process,[16)] heavy reduction is applied continuously to the bloom by movable upper and lower anvils (**Fig. 10**). The idea of applying large deformation to the unsolidified shell has a long history and has been researched in the form of an in-line rolling process for bars and rods,[17)] but this process had the inherent problem of causing internal cracks when deformation exceeded a critical strain at the solidification front. Because this critical strain is an inverse function of the thickness of the solidified shell, a process with large deformation, such as continuous width changing during castinng, is possible in the mold, where the solidified shell is comparatively thin, but was difficult to apply to the final stage of solidification. To avoid this problem, the continuous forging process has, as its characteristic features, the application of a large amount of deformation in a short-time using large anvils.

The most important feature of the continuous forging process is that it is possible to control the degree of centerline segregation arbitrarily and to induce negative segregation along the central axis when required (**Fig. 11**). For example, it was possible to improve the product

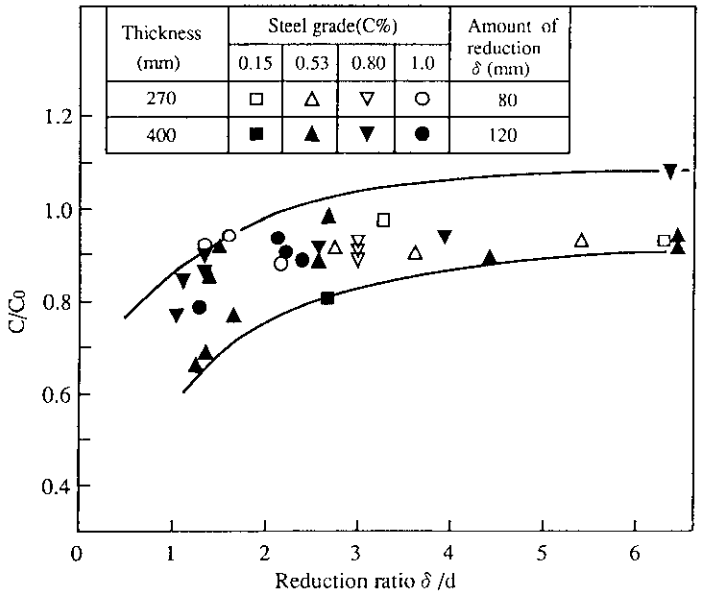

Fig. 11 Effect of reduction ratio ($\delta/d$) on centerline segregation ($\delta$; amount of reduction, $d$; thickness of unsolidified region)

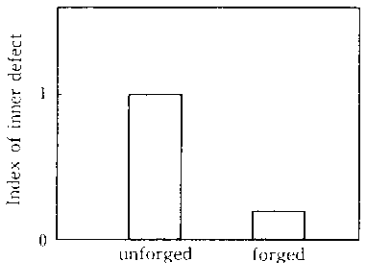

Fig. 12 Effect of continuous forged method on internal quality of 5% Cr seamless tube

characteristics of PC wire and tire cord by controlling the central carbon content to 0.72%.[18] An analysis of this process has also led to progress in the quantitative understanding of the phenomenon of molten steel flow at a high fraction of solid, which had previously been understood only in a semi-quantitative manner.[19]

Continuous forging has also proven an effective solution not only to problem of centerline segregation, but also to the problem of centerline porosity in 5% Cr billet product for seamless tubes and similar materials (**Fig. 12**).[20]

### 3.3 Examples of Progress in Product Quality Improvement

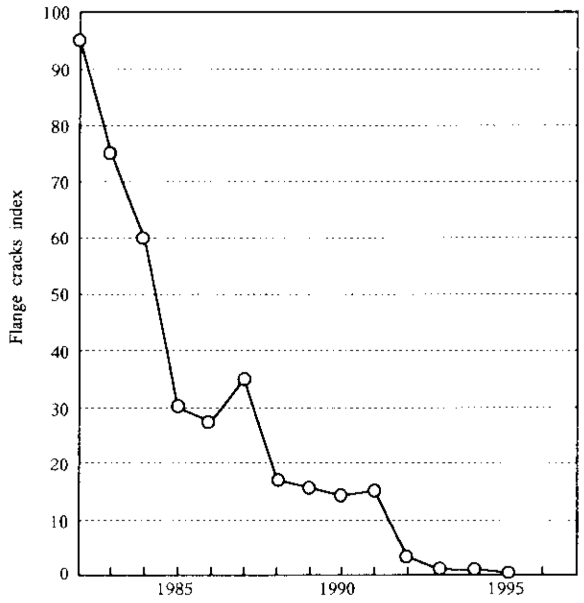

Fig. 13 Reduction of flange cracks index in DI can

Besides described major techniques for achieving high product quality, a number of other techniques have also been developed. For example, the refining of molten steel with a high level of cleanliness which include outflow detection of converter slag and ladle slag, slag refining of ladle slag, and complete tundish sealing. As a total evaluation of these respective development efforts, **Fig. 13** shows the trend in the rate of flange crack defects in drawing and ironing (D&I) cans. Because cluster type inclusions under 50$\mu$m are a problem in D&I cans, all measures have been applied to achieve high cleanliness, and resulted in a solution of the problems.

As another example, strict checks for surface defects are increasingly required with materials for exposed auto panels, such as high image clarity sheets (repre-

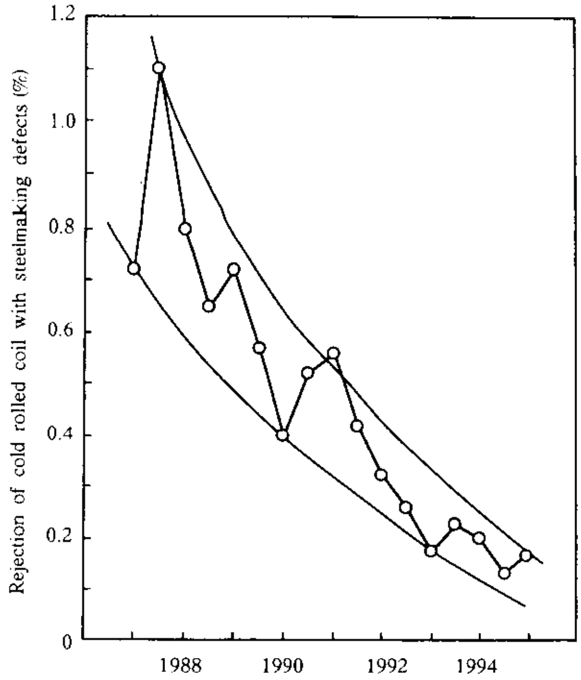

Fig. 14 Improvement of surface quality of cold rolled coil with steelmaking defects

sented by Kawasaki Steel's Laser Mirror). Thoroughgoing control of the reoxidation phenomenon and the improvement of deoxidation methods and mold powders have resulted in a dramatic reduction in the rate of cold-rolled steel defects attributable to the steelmaking process, as shown in **Fig. 14**; in the past seven years, this figure has been reduced to 1/7 of the former level.

## 4 Conclusion

During the last ten years, the requirements placed on the continuous casting process have been concentrated on high productivity, production of high-quality slabs, and linkage with the follwing process. As a method of improving productivity, continuous casting technology for super-long sequences, centering around hot tundish recycling, has achieved a stable working ratio of 92%. Techniques for quality improvement and high-speed casting such as the electromagnetic flow control mold (FC Mold) have made possible maximum casting speeds as high as 2.5 m/min, and the use of automatic hot slab transport cars allows DHCR with charging into the reheating furnace at temperatures of more than 850°C. Element technologies have also been developed to secure high quality through the entire section of the cast product from the surface to the core, with the FC mold and continuous forging process for blooms as key techniques, resulting in a dramatic decrease in flange crack defects in D&I cans and in the rate of cold-rolled coil defects attributable to the steelmaking process.

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