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Advances in High-Purity IF Steel Manufacturing Technology

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Abstract:

To meet the growing demand for corrosion resistance in automotive steel sheets, hot-dip galvanized steel sheets and other coated steel sheets have gained importance in recent years. Developed as material for coated steel sheets, interstitial-free (IF) steel has drastically increased in production. The IF steel is different in properties from conventional steels. Particularly, slivers, blowholes, and other defects originating in the steelmaking process tend to be carried into end products. After extensive investigations and analyses of these defects, Nippon Steel Corporation has overcome all of them through appropriate countermeasures, and established an IF steel mass production system. This paper describes the development efforts expended by Nippon Steel in the steelmaking field with the aim of establishing a system of stably manufacturing IF steel with high product quality.

1. Introduction

Automotive steel sheets have made a remarkable switchover from cold-rolled steel sheets to coated steel sheets, such as hot-dip galvanized steel sheets, to meet the growing demand for higher corrosion resistance. Interstitial-free (IF) steel with its excellent forming and aging properties is most suited to the process of continuous annealing, galvanizing and alloying in sequence. The IF steel is becoming a mainstream coated steel, partly because it can be mass-produced thanks to the progress of steelmaking technology including vacuum degassing. As the demand for corrosion resistance mounts, appearance-critical automotive parts (exposed panels) with severe inspection criteria are increasing in both the quantity and ratio of IF steel use to its total automotive use. The IF steel has properties different from those of conventional steels. So, it is difficult to manufacture this kind of steel simply by modifying the traditional steelmaking technology. Nippon Steel Corporation, on the strength of its accumulation of mass-production technology with stable quality assurance, has established an IF steel mass production technology.

This paper introduces the present state and future prospect of the IF steel manufacturing technology centering around the issues of quality enhancement and mass production setup.

2. IF Steel

IF steel is a high-purity steel that has minimum contents of carbon and nitrogen, interstitial solute elements, and further has solute carbon and nitrogen completely removed from the matrix by adding titanium and niobium in amounts greater than their equivalent amounts. This type of steel exhibits unparalleled properties, such as low yield point, non-aging properties, large total elongation, and high plastic strain ratio, and is suited for production on a continuous annealing line and hot-dip galvanizing line. At the start of its commercial production, however, the IF steel developed such surface defects as blowholes and slivers shown in **Photo 1**, thus lowering its production yield compared with low-carbon aluminum-killed steel. The causes of these surface defects were clarified, and corrective measures were developed against them, thereby improving the quality of IF steel.

Among the defects posing problems with IF steel, the blowhole

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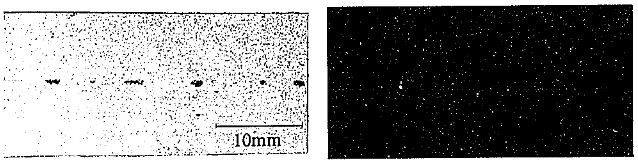

(a) Blowholes (b) Slivers

Photo 1 Examples of defects observed on IF steel product

is a swelling defect that occurs on the steel sheet surface and contains argon gas. The mechanism of their formation may be postulated from their locations and through comparative investigation on continuously cast slabs. During the continuous casting of IF steel, argon is injected to prevent the clogging of the immersion nozzle and is entrained into the molten steel in the mold. This argon is entrapped in the accumulation zone near the narrow face of the strand where the downward velocity of the molten steel balances the floating velocity of the argon bubbles. During the rolling, the bubble pressure increases and produces blowholes.

Slivers that occur in linear forms on the steel sheet surface are considered to result from inclusions exposed on the steel sheet surface. They are presumed to arise from the exposure during rolling of the alumina and powder inclusions as well as the bubbles containing them that are entrapped in the subsurface of the solidifying shell near the immersion nozzle where the molten steel flow is stagnant.

The surface defect problem of IF steel has many factors related to rolling and later processes, such as low material hardness tending to promote defect formation, and such harsh post-rolling treatments as coil coating and pre-shipping inspection. Further, increasing strictness in quality requirements calls for a scrutiny into even a very small defect. Therefore, the manufacturing conditions of IF steel are strictly controlled within optimum limits in order to ensure the desired quality. In the steelmaking process, the IF steel exhibits phenomena that are not seen with the conventional low-carbon aluminum-killed steel. These phenomena cannot be properly addressed by the traditional aluminum-killed steel manufacturing technology, resulting in an increase in the incidence of defects as compared with the low-carbon aluminum-killed steel, as shown in **Fig. 1**. This may be attributable to the innate characteristics of the IF steel, namely, a ultralow carbon content and addition of titanium and niobium to tie up the solute elements. On this point, a more detailed discussion follows:

First, the IF steel is more liable to cause immersion nozzle blockage than the low-carbon aluminum-killed steel. The immersion nozzle is progressively plugged with extending sequence casting. The molten steel discharged from the nozzle becomes nonuniform, creates a strong downward flow pattern, sends large bubbles deep into the strand pool, and accelerates the formation of blowholes. The bath level fluctuation also steps up to increase the entrapment of the mold powder and the incidence of slivers. This is probably because the IF steel, being an ultralow carbon steel, is high in the oxygen content; titanium in the steel reacts with the nozzle refractories, causing an alumina buildup on the nozzle wall.

Second, the mold powder is apt to degenerate through the reaction of its silicon oxide content with the titanium in the steel. A resultant increase in its TiO_2 content reduces its viscosity, which causes it to be entrapped in the strand being cast, ultimately to appear as slivers in the cast steel.

Third, bubbles and inclusions tend to be entrapped in the solidifying shell. IF steel, being an ultralow carbon steel, is high in the solidification temperature, and the difference between its liquidus temperature and solidus temperature is small. The result is that its mushy zone is very thin, which means that the progress of solidification is fast. For these reasons, floating bubbles and inclusions are readily entrapped in the solidifying shell. Mold oscillation forces the tip of the initially solidifying shell into the subsurface of the strand, and the resultant solidified hooks are liable to entrap bubbles, as shown in **Photo 2**. The solidified hooks in the IF steel are deeper buried than those in the low-carbon aluminum-killed steel, which has the particular effect of promoting the entrapment of inclusions and bubbles. An obvious result is an increase in the number of bubbles entrapped in the accumulation zone and subsurface to encourage the occurrence of blowholes and slivers in the cast.

Clarifying the relationship between the quality properties and manufacturing conditions of the IF steel is important in developing technology to prevent inclusion-caused surface and internal defects. The need for new measures against bubble entrapment in addition to conventional measures to counter powder and alumina inclusions was identified, and such measures were implemented accordingly.

3. IF Steel Manufacturing Technology at Nippon Steel

Nippon Steel's IF steel production has rapidly grown with soaring demand for coated steel sheets in the automobile industry, to nearly three million tons per year by now, as shown in

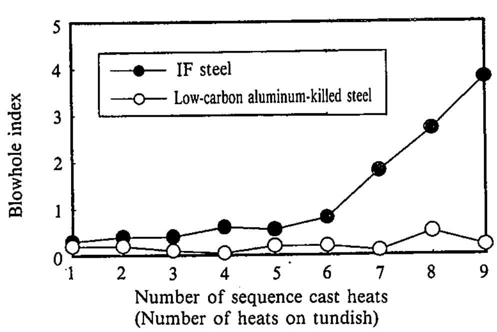

Fig. 1 Difference of blowhole occurrence by steel grade

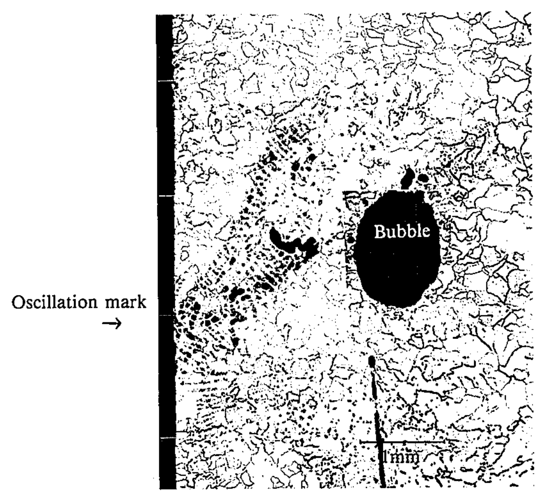

Photo 2 Bubble entrapped at oscillation mark

Fig. 2. Nippon Steel organized a companywide working group to solve problems associated with the increasing production volume of and growing severity of quality requirement for IF steel. For example, **Fig. 3** shows measures taken to cope with the mass production and quality requirement issues of IF steel at Nagoya Works. These measures are all based on the clarification of the mechanisms of occurrence for quality defects according to the peculiar properties of the IF steel described above. These countermeasures to quality defects were carried out via both routes of improving the quality building technology and intensifying the quality assurance function according to the operations control criteria. Nippon Steel now has an established IF steel production system to satisfy every customer need.

Table 1 shows Nippon Steel's IF steelmaking processes. In the refining furnace and continuous caster tundish, thorough molten steel cleaning measures are implemented to reduce alumina inclusions that directly cause slivers and indirectly cause blowholes and slivers through nozzle clogging. Among the measures con-

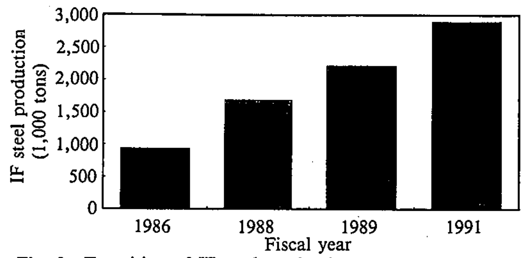

Fig. 2 Transition of IF steel production at Nippon Steel

Table 1 IF steelmaking process at Nippon Steel

Step	Function	Aim	Measure
Hot metal pretreatment	Dephosphorization	Reduction in BOF slag volume	Hot metal dephosphorization
BOF	Blowing	Reduction in alumina formation	Turndown carbon control
	Tapping	Reduction in slag carryover	Slag stopper or slag ball
Secondary refining	Ladle	Prevention of refractories contamination	Nonoxidizing refractory
	Slag treatment	Reduction in sources of slag oxidation	Plasma heater
	RH degassing	Reduction in alumina formation	Pre-deoxidation oxygen control
		Promotion of inclusion flotation	Recirculation time control
Continuous casting	Ladle shroud	Prevention of slag entrapment	Submerged opening
		Prevention of slag carryover	Stopper, slag carryover detection
	Tundish	Prevention of air oxidation	Shielded tundish
		Prevention of contamination by insulating material	SiO_2-free insulating material
		Constant-temperature operation	Plasma or induction heating
		Prevention of slag entrapment	Tundish shape
		Promotion of inclusion flotation	H-shaped tundish
	Immersion nozzle	Prevention of powder entrapment	Argon flow rate and pressure control
		Prevention of inclusion penetration	Nozzle shape
		Prevention of nozzle clogging	ZrO_2-CaO and / or SiO_2-free refractories
	Mold	Prevention of powder entrapment	High-viscosity powder
		Prevention of powder entrapment	Mold bath level control
		Prevention of entrapment in surface layer	Oscillation control
		Prevention of entrapment in surface layer	In-mold electromagnetic stirring
		Prevention of entrapment in accumulation zone	Vertical bending caster

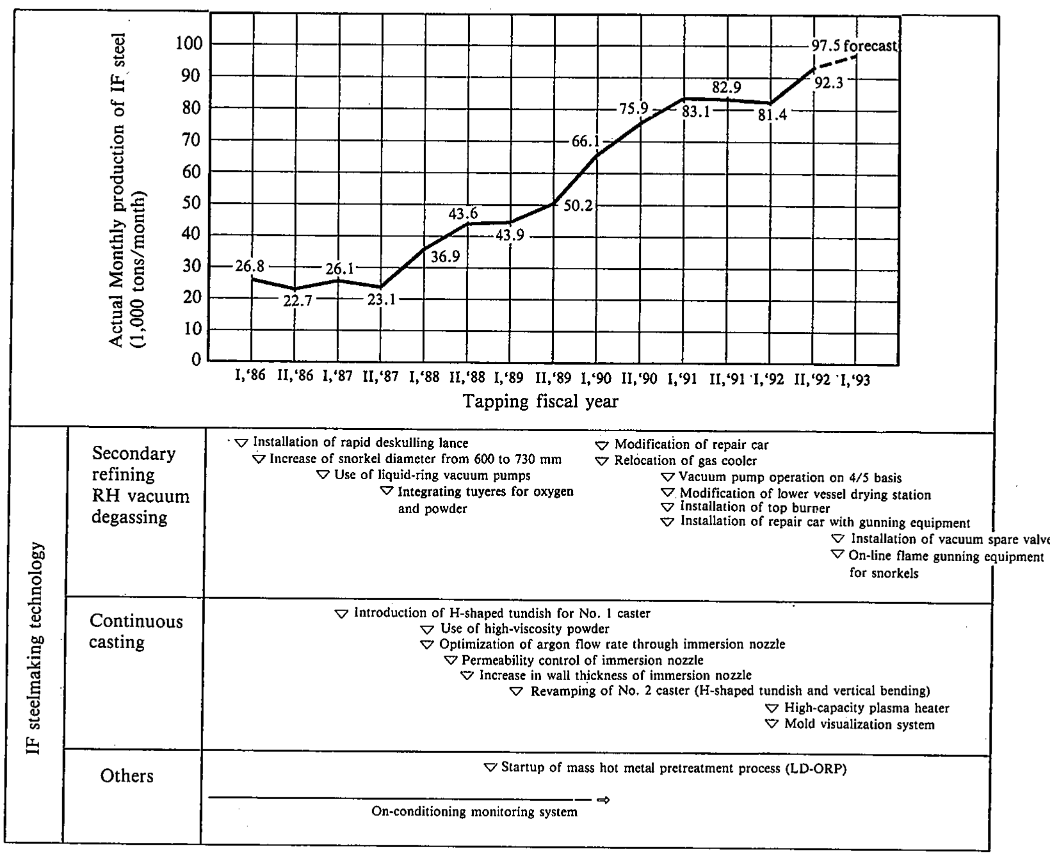

Fig. 3 Transition of IF steel production and main IF steelmaking technologies at Nagoya Works

ventionally taken to alleviate the effects of slag, refractories and air as sources of oxidation for the molten steel are reduction in BOF slag carryover, modification of ladle slag, use of nonoxidizing refractories, control of the oxygen content with the RH vacuum degasser, complete shrouding of the tundish, submerged opening of the ladle shroud, and use of nonoxidizing tundish insulating material. In addition, the hot metal pretreatment process reduces the volume of the BOF slag. In particular, thoroughgoing slag modification is effected by plasma heating ladles at Hirohata Works. RH treatment and tundish shape optimization have been carried out to enhance inclusion floatation and removal. The large H-shaped tundish introduced at Nagoya Works is characterized by long molten steel flow path and simultaneous pouring from two ladles during a ladle change. The former measure is designed to promote inclusion flotation, and the latter to prevent the ladle change portion from deteriorating in cleanliness. These measures have helped to reduce slivers arising from alumina inclusions.

Also from the viewpoint of preventing immersion nozzle clogging, the vital problem of sequence casting, tundish induction heating and plasma heating were introduced to reduce the unsteady-state condition at ladle changes. Further, a ZrO_2-CaO-C immersion nozzle was developed to reduce alumina buildup through the formation of a low-melting point layer, as shown in **Fig. 4**. A silica-free alumina graphite nozzle with little refractory deterioration has been developed and is being introduced in practical application[1]. These comprehensive measures now allow many heats to be sequence cast without suffering blowhole incidence even after prolonged sequence casting.

Next, in continuous casting, it is also important to prevent the entrapment of the mold powder. A high-viscosity powder was developed that can maintain its viscosity while in contact with the molten steel so that it cannot be easily entrapped in the molten steel. Among the operational measures introduced were the aforementioned nozzle clogging prevention, optimization of the argon gas flow rate, stabilization of the mold level, and operational control by an on-line monitor. These measures have sharply reduced powder-caused slivers. Furthermore, mold oscillation is optimized to reduce the oscillation marks that are related to the above-mentioned solidified hooks inducing slivers. Nagoya Works independently controls the amplitude and frequency of mold oscillation according to the casting speed by a mold oscillator with hydraulic stepping cylinders.

Stirring the molten steel at the meniscus near the immersion nozzle where the molten steel flow is weak is effective to prevent the entrapment of bubbles and inclusions. Its effectiveness in reducing the incidence of slivers is now confirmed as shown in **Fig. 5**, and accordingly in-mold electromagnetic stirrers are being introduced[2].

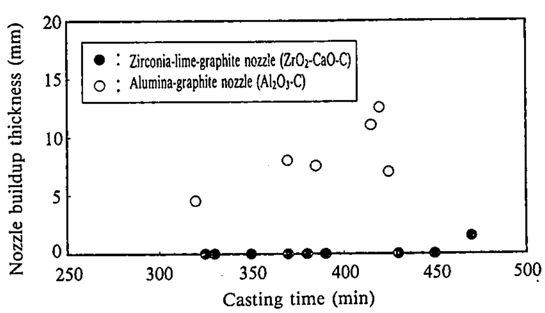

Fig. 4 Effect of zirconia-lime-graphite immersion nozzle on reducing buildup

A continuous caster of the vertical bending type having an upper vertical portion was introduced as one method to optimally control the discharge flow from the immersion nozzle. This type of continuous casting machine optimizes the nozzle port diameter and angle, and is based on the concept that a vertical solidification field in the form of a straight mold is fundamentally ideal for the phenomenon of bubbles and inclusions floating in the gravity field. An example of the effects of vertical bending-type casting is shown in **Fig. 6**. The vertical bending design can drastically reduce the number of bubbles and blowholes in the cast.

Table 2 shows the transition in Nippon Steel's IF steel production, number of heats sequence cast per tundish, casting throughput, and integrated production yield. The measures described above have raised the casting throughput and the number of sequence cast heats to meet the demand for IF steel mass production. Quality of IF steel comparable to that of low-carbon aluminum-killed steel, which was initially predicted to be essentially difficult, has been achieved by various quality building techniques. For example, the integrated yield of IF steel for automobile exposed panels with particularly stringent quality requirement is now more than 10% higher than the initial level and is close to that of low-carbon aluminum-killed steel.

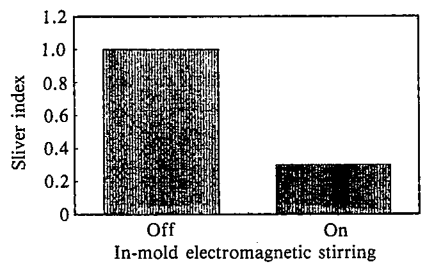

Fig. 5 Effect of in-mold electromagnetic stirring on reducing slivers

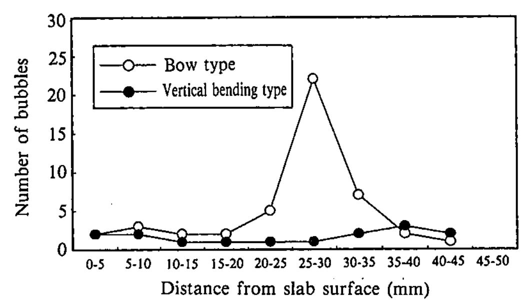

Fig. 6 Effect of vertical bending-type continuous caster on reducing number of bubbles in slabs

Table 2 Changes in IF steel production data at Nippon Steel

Year	1988	1989	1991
IF steel production (1,000 tons)	1,690	2,220	2,900
Number of heats on tundish	4.81	5.01	5.48
Maximum casting throughput (t/min)	4.1	5.0	5.6
Overall yield (%)	72.9	79.4	83.7

4. Future Trend of IF Steel Manufacturing Technology

IF steel has increased in production in a short period as material for automobile exposed panels that are subject to strict quality requirements. Since it involves peculiar solidification phenomena, IF steel has been continuously cast under various direct and indirect operational control constraints that may seem excessive compared with conventional low-carbon aluminum-killed steel. How to control what operation parameters is being clarified in relation not only to operation data but also to such phenomena as defect occurrence mechanisms involved. When the measured data fail to meet the applicable control standards, the cast IF steel is diverted to a lower grade application according to the conventional quality assurance system. Given the recent trends of quality throughput and process integration, however, the effect of this diversion system on the production of other steel grades cannot be ignored.

In view of the current trend toward low-cost mass production and added severity in quality requirements, the conventional quality control system for IF steel that is based on overall operations control involving abnormality rejection should be replaced by more rational systems of: quality assurance with the backing of process-to-process quality building technology; yield enhancement through manufacturing process integration; and delivery lead time shortening by streamlining the material flow.

One of the measures to be taken in the above challenges is for field operators to adequately grasp operational transitions from time to time and to control operations in real time in order to provide optimum conditions for IF steel according to the information obtained. In other words, an on-line real-time operation monitoring system is essential for successful IF steel production.

Focusing on the above concepts and placing utmost importance on in-mold molten steel flow control, Nippon Steel has carried out the development and application of in-mold molten steel flow control. For example, an "on-condition monitoring system" was introduced about 10 years ago at Nagoya Works. The system calculates important parameters concerning in-mold molten steel flow by a simulation model from mold surface thermocouple readings and mold level fluctuations, and displays the measured data and their calculated results to the operator through CRT screens. More recently, this "on-conditioning monitoring system" has been extensively modified to display information concerning the molten steel flow in the mold, such as flow rate of molten steel discharged through each nozzle port, molten steel velocity at the meniscus, thickness of the narrow-face solidifying shell just below the mold and penetration depth of molten steel into the strand pool, in addition to the conventional mold level fluctuation, biased flow of molten steel in the mold and immersion nozzle clogging factor. This "mold visualization system" is developed and used that can not only present mold information in a more accurate and comprehensive manner, but also graphically show whether the current operating conditions are appropriate or abnormal. Typical examples of display screens are given in **Fig. 7**.

These technologies make it possible to quickly detect any conditions that could lead to quality or operational troubles. With such information, the casting operation can be adjusted to meet specific steel grades by best utilizing the aforementioned functions of heating the tundish, electromagnetically controlling the molten steel in the mold, and controlling casting speed, immersion nozzle argon flow rate and other casting parameters.

IF steel has posed many problems in the steelmaking process because of its severe quality requirement, while solution of such problems has prompted the refinement of IF steelmaking technology centered on the assurance of specified quality for the downstream processes. Nippon Steel will continue to work on the establishment of technology for stably manufacturing higher quality IF steel.

References
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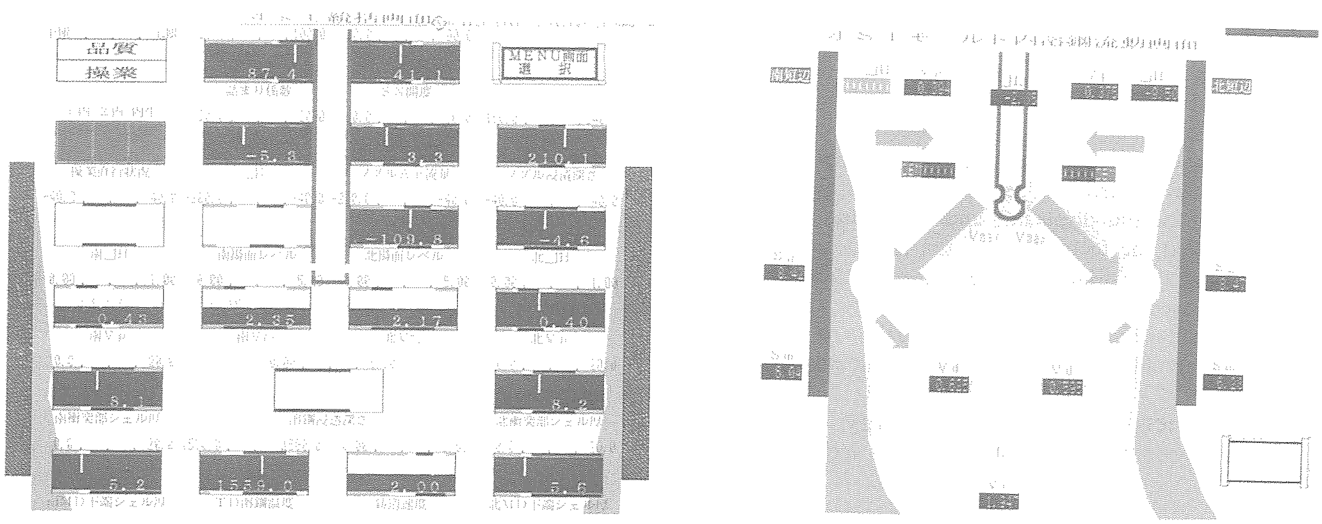

(a) (b)

Fig. 7 Master and individual display screens of mold visualization system (Example)