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Innovative Technologies in Continuous Casting Tundish

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Abstract:

Continuous casting is considered the final stage of evolution in steelmaking, and, as it directly influences the quality of end products, has important roles to play in connection with the growing severity in quality requirement, product sophistication, price competitiveness, and the flexibility of production lot determination. Against this background, Nippon Steel has worked on the development of a multifunctional tundish with which to perform a refining function in the continuous casting process. This article describes: 1) formulation and application of a model for estimating the behavior of inclusions in the tundish; 2) high-capacity tundish steel heaters on mass-production continuous casters; 3) tundish hot turnaround; 4) flexible small-lot production with composition adjustment in the tundish. The future prospect of tundish technology is discussed at the end.

1. Introduction

In the continuous casting process, an intermediate vessel called the tundish is installed between the molten steel ladle and the mold. The tundish traditionally has roles of a distributor of molten steel to molds, a buffer to ensure uninterrupted molten steel feed during a ladle change, and a vessel to facilitate the flotation and removal of inclusions. The tundish is gradually increasing in size to meet the growing stringency in steel quality requirements and is diversifying in functions to meet more flexible lot production. In this connection, Nippon Steel has worked to clarify the phenomena occurring in the tundish and to put obtained findings to use in adjusting the molten steel in the tundish. This article describes: 1) development and application of a model to study the behavior of inclusions in the tundish; 2) high-capacity tundish steel heaters on mass production continuous casters; 3) tundish hot turnaround; and 4) flexible production lot composition through the operation of tundish steel refining. The future trends of tundish technology are discussed at the end.

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2. Study on inclusion behavior in the tundish

The stable production of clean steel requires tundish metallurgy, that is to say, the quantitative understanding of the mechanism of inclusion behavior in the tundish steel. In the usual approach to the behavior of inclusions in the molten steel in the tundish, attention was focused only on the flotation removal of inclusions. However, recent results of steel cleanliness investigations show that this approach is not sufficient. It cannot fully explain the change with time in the actual steel cleanliness along the strand, particularly in such unsteady-state portions as ladle change portions. It appears necessary also to take into account the steel contamination in the tundish.

2.1 Formulation of tundish inclusion behavior model

Generally, tundish operating standards are stratified by strand position in relation to the steady-state and unsteady-state heat portions. Examination of surface and internal defects in steel products indicates deteriorating quality in unsteady-state strand portions. The tundish inclusion behavior model[1] illustrated in **Fig. 1** was developed in order to quantitatively determine the contamination and cleaning of the molten steel in the tundish, particularly during a ladle change. Four factors are considered responsible for the contamination and cleaning of the molten steel in the tundish near a ladle change. The model assumes that the contamination of the molten steel by factors ① to ③ proceeds at the same time as the cleaning of the molten steel by factor ④ and that the cleanliness of the molten steel at the tundish outlet depends on the effect of each factor concerned. Factors ③ and ④ are considered to have a large impact in the steady-state portions and factors ① and ② in the unsteady-state portions.

2.2 Quantitative analysis of tundish steel cleanliness

The cleanliness of molten steel was analyzed on No. 1 continuous caster (with two strands and a 60-ton tundish) at Yawata No. 3 steelmaking plant to grasp factors responsible for the contamination of molten steel in a conventional boat-shaped tundish and to quantify their respective contribution rates as computed with the above-mentioned tundish inclusion behavior model[2].

2.2.1 Methods

The experimental conditions are shown in **Table 1**. The first of three heats of low-carbon aluminum-killed steel was cast under such conditions that the ladle sliding nozzle sand and ladle slag should not flow into the tundish. The tundish steel was sampled at both the ladle long nozzle position (tundish inlet) and the tundish immersion nozzle position (tundish outlet). The samples were examined by optical microscopy to count 10 μm or larger inclusions by shape (cluster, lump or globular) and size, and were examined also for composition by an electron-probe microanalyzer (EPMA).

2.2.2 Results

(1) Composition of inclusions in tundish

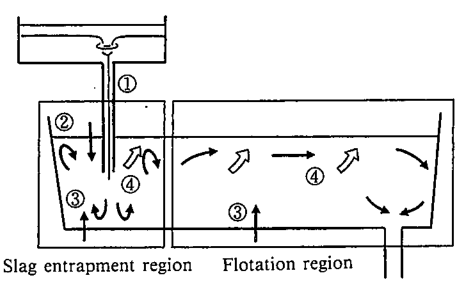
When the composition of inclusions in the tundish was examined by the EPMA, clustery and lumpy inclusions were Al_2O_3, and globular inclusions were mostly CaO-Al_2O_3 and rarely Al_2O_3. **Fig. 2** shows the composition of globular inclusions at the tundish inlet and outlet. The globular inclusions can thus be taken as ladle slag carried over into the tundish. (Hereinafter the clustery and lumpy inclusions are referred to as alumina inclusions, and the globular inclusions as slag inclusions.) From **Fig. 2**, the change of inclusion chemistry from the tundish inlet to outlet are known to be relatively small. At the tundish outlet, the MgO concentration increases, probably from the tundish refractories, but the increase is a mere 4% or so, indicating that the refractory wear is negligible.

(2) Number of inclusions in tundish

Fig. 3 shows the change in the number of alumina and slag inclusions over the three heats. The number of alumina and slag inclusions at the tundish inlet increases with increasing number of heats. Within the tundish, the slag inclusion count made a similar change at both the inlet and the outlet, with the outlet count indicating a slight decrease from the inlet count. This suggests that some of the slag inclusions introduced into the tundish were removed by flotation. The number of alumina inclusions increases in the tundish, probably because of the reduction of oxide slag and ladle sand by aluminum in the molten steel, and the oxidation of the molten steel by air.

2.2.3 Discussion

The simultaneous cleaning and contamination of the molten steel at the tundish inlet as expressed by Eq. (1) are considered to quantitatively evaluate the effect of the factors responsible for the contamination of the molten steel in the tundish. The number of 10 μm and larger inclusions counted by optical microscopy is converted into the corresponding inclusion concentration and presented as an index of steel cleanliness.



Factor	Characteristic
①Ladle molten steel cleanliness	Slag carryover at end of ladle pouring
②Molten steel contamination at tundish inlet point	Slag entrapment at start of pouring from next ladle heat
③Other contamination	Oxidation of aluminum in molten steel by slag insulating material, air, etc.
④Inclusion flotation and removal	

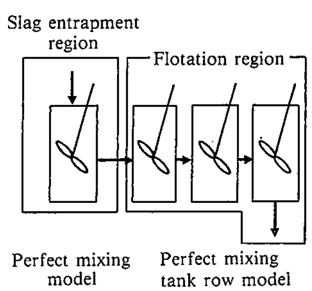


Fig. 1 Tundish inclusion behavior model

Table 1 Plant test conditions

Heat size	320 ton/heat
Sequence casting	3 heats/cast
Casting conditions	1st heat: First 10 ton and last 20 ton were not cast 2nd and 3rd heats: Entirely cast
Tundish shield	Argon injection (to about 0.05 atm of P_{O_2})
Tundish flux	MgO
Tundish coating material	MgO
Slag composition	FeO = 5%

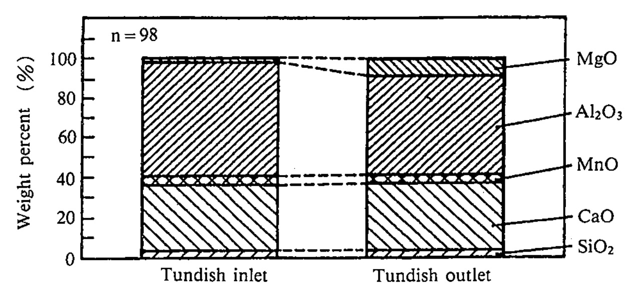


Fig. 2 Composition of slag-based inclusions in tundish

Cleanliness of molten steel at tundish outlet
= Cleanliness of molten steel at tundish inlet + Amount of contamination in tundish..(1)
where,
Cleanliness of molten steel at tundish inlet
= Σ(Area fraction of inclusions by size × Residual ratio of inclusions by size in tundish)

(1) Flotation ratio of inclusions by size

The flotation ratio of inclusions by size was calculated from the change in the number of slag inclusions between the tundish inlet and outlet shown in **Fig .3**. The results are given in **Fig. 4**. As can be seen from **Fig. 4**, the flotation ratio increased with increasing size, and 200 μm and larger inclusions were almost completely floated and removed in the tundish.

(2) Quantitative determination of factors responsible for contamination of molten steel in tundish

The theoretical and measured cleanliness of molten steel at the tundish outlet are compared in **Fig. 5**. The difference indicates the amount of contamination from the tundish inlet to the outlet. The in-heat change with time in the theoretical molten steel cleanliness is the change with time in the amount of contamination at the tundish inlet.

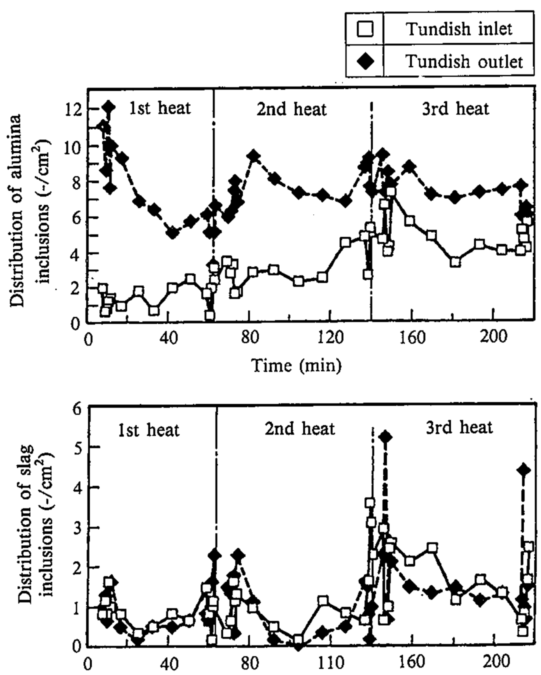


Fig. 3 Change in number of inclusions (> 10 μm) in tundish

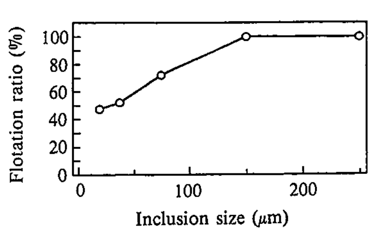


Fig. 4 Effect of inclusion size on inclusion flotation ratio

(i) Oxidation by Air

The difference between the measured and theoretical molten steel cleanliness at the tundish outlet, calculated from **Fig. 5**, is shown in **Fig. 6**. Oxidation by air of the molten steel, reaction between the ladle slag carried into the tundish and the molten steel in the tundish, and tundish refractory are listed as factors responsible for the contamination of molten steel in the tundish. As already discussed in connection with **Fig. 2**, oxidation by air is the prime factor in the contamination of molten steel in the tundish. The amount of oxidation by air is almost constant in the steady-state portion within a heat, but increases at the start of the first heat and during a ladle exchange. The oxidation by air is presumed to affect each heat for nearly two-thirds of the casting time.

(ii) Ladle slag and sand

The theoretical cleanliness of the molten steel at the tundish outlet is shown in **Fig. 6**. As shown, contamination is slight in the first heat where the carryover of the ladle slag and sand is prevented, and remains stable at the constant level in the heat.

Contamination increases up to one-third of the second heat, indicating the contamination of the tundish steel by ladle sand (98% SiO_2) carried over into the tundish. Contamination then decreases, but increases again near the end of the second heat, probably owing to the carryover of ladle slag. In the third heat, the accumulation of ladle slag adds to the amount of contamination in the second heat, and contamination follows practically the same tendency in the second heat.

2.3 Measures for improving cleanliness of molten steel in tundish

The tundish inclusion behavior model and the plant tundish steel cleanliness survey discussed above point to the importance of controlling the carryover of ladle slag and sand into the tundish and preventing the oxidation by air of the tundish steel in addition to the flotation removal of inclusions as conventionally

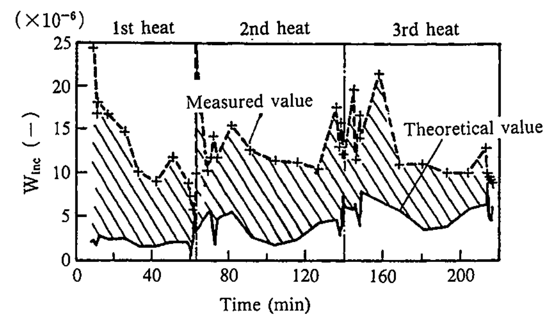


Fig. 5 Change in cleanliness of molten steel in tundish during sequence casting

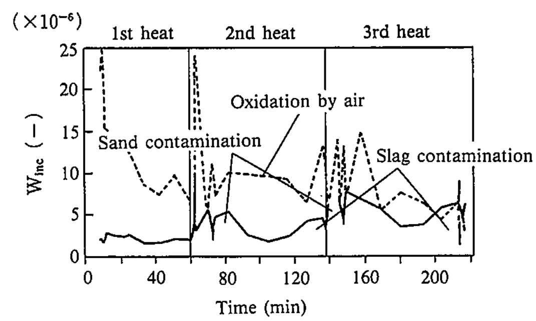


Fig. 6 Effects of oxidation by air and slag contamination on amount of inclusions during sequence casting

done for clean steel production. Nagoya Works introduced an H-shaped tundish. This tundish is designed to provide the molten steel with a long path to facilitate the flotation of inclusions by a two-vessel tundish structure, and to pour the molten steel simultaneously from two ladles at a ladle change (to pour the molten steel with moderate throughput even at a ladle exchange) for rendering harmless the ladle slag and sand carried over into the tundish. It proved effective in sharply reducing the slag contamination of the tundish steel. A sensor for detecting the carryover of ladle slag into the tundish and a tundish shield for completely preventing the oxidation by air of the molten steel have been introduced at various works and are becoming standard equipment for continuous casters.

3. Recent Innovation in Tundish Technology

Besides the technologies for steel cleanliness in the tundish as described above, Nippon Steel undertakes various development works on innovative tundish technologies for: 1) high-capacity heating of molten steel on a mass production continuous caster; 2) hot turnaround of tundishes; and 3) flexible production lot composition through the tundish operation. These new technologies on continuous casting, some of which are already being commercialized at various works of Nippon Steel, are outlined below.

3.1 High-capacity tundish steel heating technology for quality improvement

Muroran and Hirohata have worked on the development of tundish steel heating technology to minimize transition (unsteady-state) portions on mass production continuous casters. Recently, a high-capacity plasma heater and an induction heater have been installed at Nagoya and Yawata, respectively. They are outlined below.

3.1.1 Plasma heating

A high-output plasma heater[3] was introduced on Nagoya No. 2 continuous caster for the purpose of precisely controlling the molten steel temperature that is directly linked to the stabilization of caster operation and slab quality.

(1) Outline of high-output plasma heater

This equipment is schematically illustrated in **Fig. 7**. Two plasma torches are installed at the longitudinal center of the second vessel of the H-shaped tundish, and are characterized by their ability to control the steel temperature to suit the casting speed of each strand. **Table 2** gives their specifications. The maximum output is 2.35 MW, and the distance from each torch to the bath surface is automatically controlled.

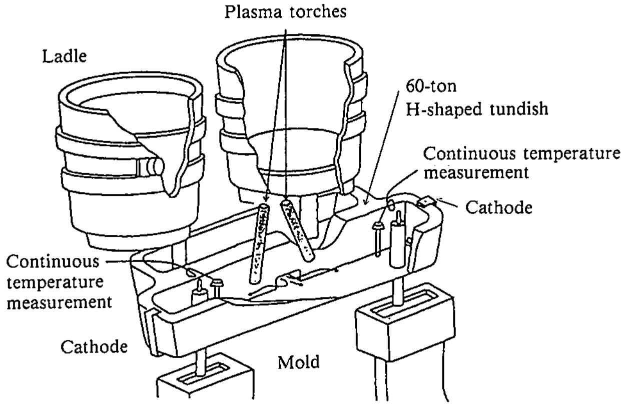


Fig. 7 Tundish plasma heater

Table 2 Specifications of plasma torch

Type	DC transferred arc
Maximum current	5,000 A/torch × 2
Maximum output	2.35 MW/torch × 2
Plasma gas flow rate	Argon 2,300 l/min × 2 Nitrogen 700 l/min × 2
Cooling water flow rate	450 l/min × 2

(2) Operation and quality improvement with plasma heating

Fig. 8 compares operations with and without plasma heating. Formerly, some steel temperature variation was unavoidable during a ladle change. Plasma heating can control the temperature variation to less than 5°C between heats during a ladle change. Plasma heating can minimize immersion nozzle clogging in low-temperature casting portions and contribute greatly to quality improvement in such high-grade sheet steel as tinplate, as indicated by the drastically reduced occurrence of internal defects in **Fig. 9**.

3.1.2 Induction heating

A tundish induction heater was introduced on No. 2 continuous caster at Yawata No. 3 steelmaking plant. The purpose was to improve the quality of IF steel and such high-grade sheet steels as tinplate by constant-temperature casting and to cast small-section blooms stably over a long casting time by temperature compensation. Based on the low-frequency induction heating system of the intermediate channel type developed at Muroran Works, this technology has been smoothly operating since January 1993. The induction heater is schematically illustrated in **Fig. 10** and its equipment specifications are given in **Table 3**. The tundish consists of molten steel inlet and outlet chambers. The molten steel is induction heated in the channel (brick sleeve) connecting these two chambers. The sleeve is made of alumina spinel refractory to assure fire proof and erosion resistance and to preclude electromagnetic induction. The induction heating input power is automatically controlled by feedback of the tundish steel temperature in the outlet chamber. **Fig. 11** shows an example of heating efficiency. The difference between the inlet and outlet chamber

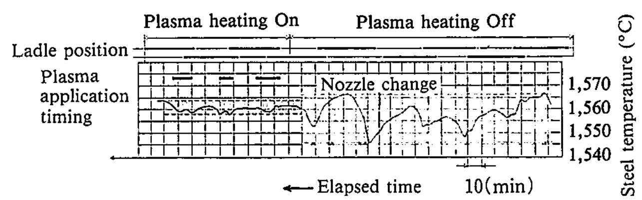


Fig. 8 Control of tundish steel temperature by plasma heating

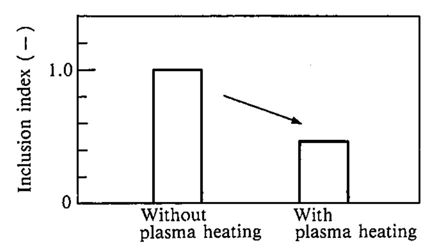


Fig. 9 Effect of plasma heating on occurrence of internal defects in steel product

steel temperatures and that between the chamber steel temperature and the ladle steel temperature increase with increasing induction heating input power. The heating efficiency is 40% for the inlet chamber, 50% for the outlet chamber, and as high as 90% for the total. **Fig. 12** shows the molten steel cleanliness at the tundish outlet during bloom casting. The cleanliness of the tundish steel is improved by tundish induction heating. This excellent performance can be attributed to the flotation of inclusions by the rising stream formed with induction heating and to the removal[4] of inclusions by the electromagnetic force (pinching force) generated by induction heating. These combined benefits of induction heating will be quantitatively determined to improve the quality of cast steel.

3.2 Introduction of tundish hot turnaround technology

In October 1992, Hirohata Works introduced tundish hot turnaround equipment to improve the quality of non-steady state portions, to drastically cut down the tundish cost, and to eliminate the "dangerous, dirty, and difficult" tasks associated with tundish maintenance.

3.2.1 Outline of tundish hot turnaround work

Fig. 13 shows the flow of tundish hot turnaround work. After the cast is completed, residual steel in the tundish is promptly removed. The immersion nozzle is pushed out by the tundish stopper and is replaced with a new immersion nozzle using an immersion nozzle exchanger. Tundish maintenance is done in a very simple flow pattern.

3.2.2 Features and main techniques of tundish hot turnaround system

Nippon Steel's tundish hot turnaround system features the following:

(1) Complete elimination of preheating

This system made it necessary to develop a technique to quickly

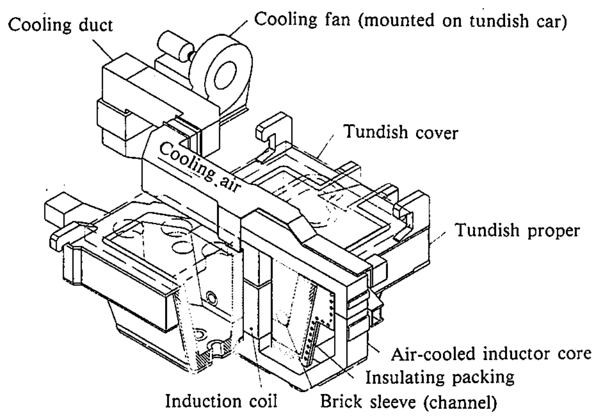


Fig. 10 Outline of induction heated tundish equipment

Table 3 Main equipment specifications

Item		Specification	
		3rd strand	4th strand
Heat size		350 ton	350 ton
Casting		Slab	Bloom
Tundish capacity		30 ton	30 ton
Heating capacity		1,000 kW	1,500 kW
Induction heating sleeve	Quantity	2	2
	Refractory	Alumina spinel	Alumina spinel
Heating control		Automatic control	Automatic control

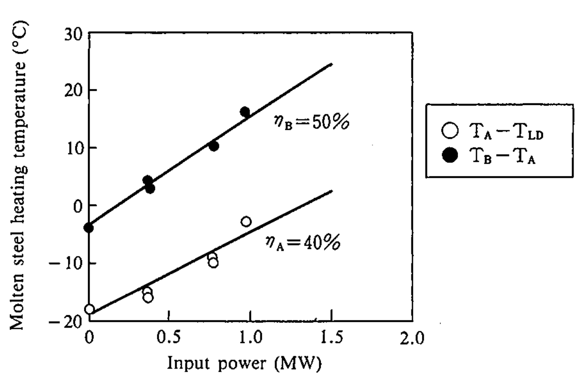


Fig. 11 Molten steel heating efficiency of induction heater

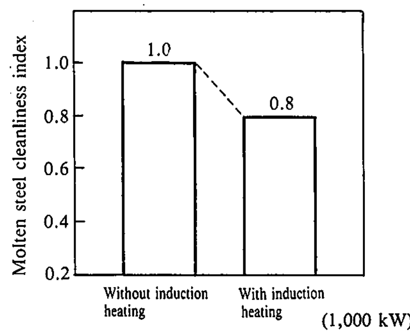


Fig. 12 Comparison of molten steel cleanliness

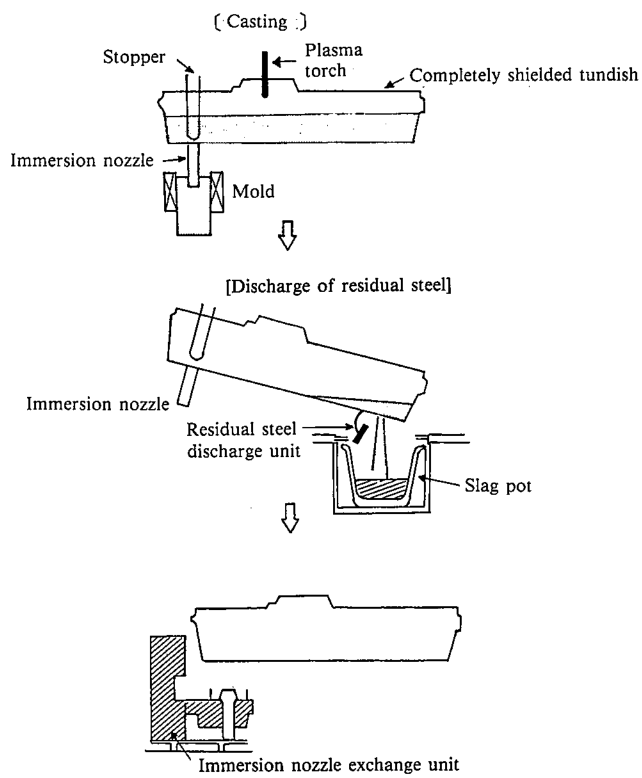


Fig. 13 Task Flow of tundish hot turnaround

change the immersion nozzle that is preheated up to 1,300°C. Hirohata Works accomplished the technique by developing a mortar having necessary high-temperature properties and making various immersion nozzle exchange devices.

(2) Protection of molten steel against oxidation with integral immersion nozzle and completely shielded tundish

This system prevents air infiltration and abolishes the use of tundish insulating material.

(3) Rapid removal of residual steel and slag

The unit discharges the residual steel to empty the tundish within 2 min by operating a flapper installed on the tundish bottom, as shown in **Fig. 14**.

3.2.3 Results of tundish hot turnaround operation

Fig. 15 shows the change in the surface temperature of tundish brick after the cast end. The brick temperature after the 40-min standby time prior to the next casting is 1,450°C, which is much higher than the temperature of 1,200°C to which the tundish was conventionally preheated after its cold repair. This means that tundish preheating can be completely dispensed with. The tundish hot turnaround system is also effective against the drop of tundish steel temperature, as shown in **Fig. 16**.

Formerly, when the hot turnaround tundish was continuously used over a long period of time, some buildup was observed. This problem was solved by applying plasma heating to the tundish steel toward the end of each cast, and lowering the melting point of slag by adding flux into the tundish. In February 1993, a continuous operation record of 561 heats per tundish was established. As a result, the tundish refractory cost has been reduced to about one-third of the previous level.

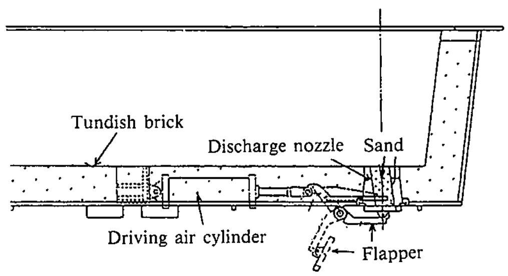


Fig. 14 Outline of residual steel discharge unit

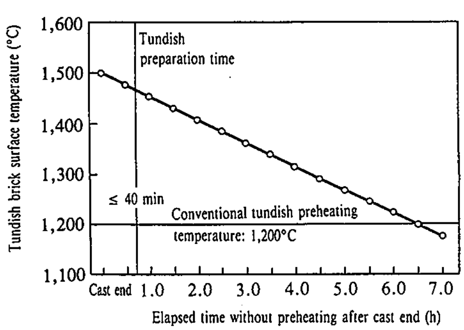


Fig. 15 Tundish brick surface temperature after cast end

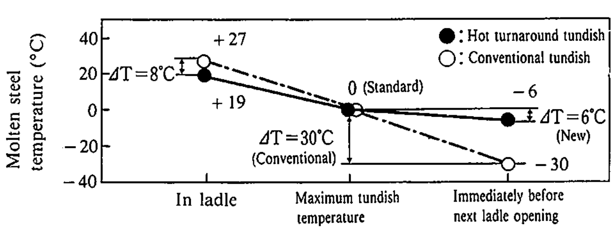


Fig. 16 Decrease in molten steel temperature drop by tundish hot turnaround system

3.3 Technology of small-lot production with induction heated tundish

With the trend of the times toward product diversification and sophistication, the customer demand for steel products calls for the small-lot production of diverse product types. By the LD converter steelmaking-secondary refining-continuous casting process, small lot production poses the problem of open-order production that raises the production cost. Against this background, Muroran Works has developed and implemented a unique small-lot production technology that best utilizes chemistry adjustment in the tundish.

3.3.1 Outline of process (alloy addition into induction heated tundish)

Small-lot steel from the LD converter steelmaking-secondary refining route is properly divided and fed into the tundish where it is processed by the thermal surplus and flux refining functions of tundish induction heating. The induction heated tundish is a key equipment for this process. Its schematic illustration is given in **Fig. 17**, and its main equipment specifications in **Table 4**. The maximum input power of the tundish induction heater is 2.0 MW, and the heating rate for stationary molten steel is 4.2°C/min when the tundish contains 20 tons of molten steel. **Fig. 18** shows the relationship between the heating time and the amount of ferroalloy that can be melted. About 2% (0.5 tons) of alloy can be melted in the heating time of 10 min.

3.3.2 Results of small-lot production

(1) Homogeneity of composition

A pattern of steel refining in the tundish is shown in **Fig. 19**. The entire treatment can be completed within 10 min from pouring into the tundish to the casting start. This example concerns the case of 0.03% and 0.30% changes in the carbon and manganese contents, respectively. The desired chemistry is accomplished within about 3 min after the alloy addition. It is thus

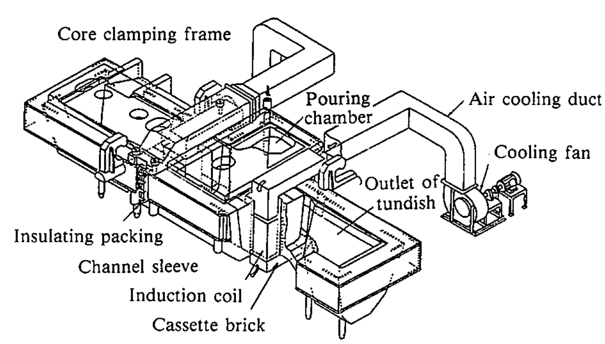


Fig. 17 Outline of tundish induction heater

Table 4 Main specifications of tundish induction heater

Item	Specification
Type	Air-cooled intermediate channel induction heating
Power capacity	1,000 kW × 2 strands
Heating capacity	4.2°C/min (for stationary molten steel)
Control method	Tap switching method

confirmed that composition homogeneity can be attained in an extremely short time.

(2) Cleanliness

Fig. 20 shows the transition of total oxygen content in the tundish steel when a large ferroalloy addition (600 kg) was made. The stirring effect of induction heating gradually reduces the total oxygen content to produce a highly clean steel.

(3) Effect on impurity contents of gaseous element

The small-lot treatment of still molten steel in the tundish is liable to involve hydrogen and nitrogen pickup from the tundish refractories and ferroalloy additions. It has been confirmed that this problem can be eliminated by controlling the moisture content of tundish refractories and the bath surface coverage with tundish flux.

3.3.3 Summary

Small-lot production technology with an induction heated tundish was developed. This technology is very effective in fulfilling small-lot orders for special steel bars and rods, and producing high-quality steels in quick response to customer needs.

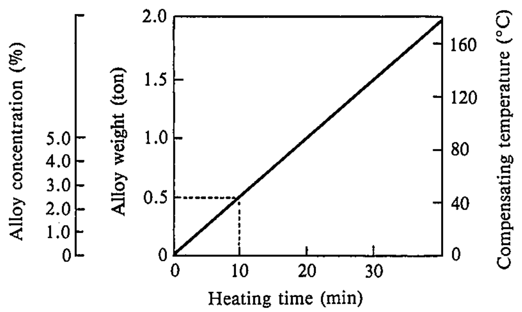


Fig. 18 Alloy addition and heating time

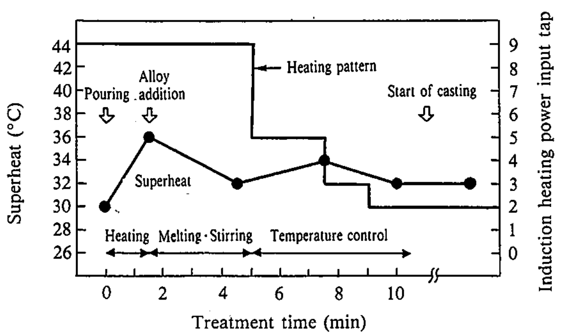


Fig. 19 Tundish steel treatment pattern

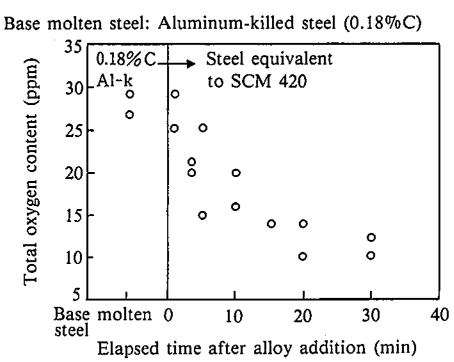


Fig. 20 Change in total oxygen content of molten steel in tundish during treatment

4. Future Outlook of Tundish Technology Innovation

The tundish technology innovation recently made by Nippon Steel have been described above. These technologies have been applied at the steelworks described here and will be transferred to other steelworks as key technologies to meet the challenges of production process integration, product sophistication, small-lot production, and workplace environment. Constructive improvements will be made to multifunctional tundishes, and such multifunctional tundishes will advance further with the prevention of ladle slag carryover, application of electromagnetic force, and monitoring of molten steel flow. Technologies will be developed also for lessening the secondary refining load, consolidating secondary refining steps, stabilizing the operation of continuous casters, and producing higher- quality steels.

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