Technical Review

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Advances in Steel Refining Technology and Future Prospects

Masanori KUMAKURA*

Abstract

To maintain cost competitiveness in the global market, meet fluctuating demand for steel products, stably produce high-end products, and adequately respond to social requirements such as regulations on fluorine in slag, reduction of CO_2 emission, and environmental conservation (intensive dust collection of plant buildings, etc.), Nippon Steel Corporation has continuously fostered wide varieties of steel refining technology. The present paper outlines the measures taken, the development of different technologies for individual processes, and the operation improvements in the field of steel refining over the last two decades, and tries to prospect future trends in the field.

1. Introduction

It was 18 years ago (1994) that the Technical Report last related to the advances in the steel refining technology and future prospects.[1] The environment surrounding the steel industry of Japan has changed significantly in the meantime; such changes include the rising of developing countries, intensifying international competition, soaring resource prices, fluctuating exchange rates, requirements for reduction of carbon dioxide emission, and regulations on fluorine use. Facing the situation, the company has continued to study and develop steel producing technology in the efforts to establish the capability to stably produce high-end products, and respond to the requirements of communities around steelworks for environmental conservation. Of the various branches of steel producing technology, this paper outlines the historical change and present state of the refining technology.

2. Historical Change in Steel Refining Technology

2.1 Challenges and responses of refining processes

The main issues in the refining processes and the orientations of technical development over the last 20 years are as follows. (1) Hot-metal pretreatment was restructured such that desulfurization was separated from dephosphorization and dephosphorization was separated from decarburization (preliminary dephosphorization of hot metal) to enhance reaction efficiency, reduce the costs of auxiliary materials, and decrease slag discharge. (2) In response to rising demand for steel, production capacity was expanded, thermal allowance was increased, flexibility in selection of feed stock was secured, and by so doing, the hot-metal pretreatment ratio was kept at a high level. (3) Refining processes free from the use of fluorine were developed vis-à-vis the regulations under the environmental quality standards for soil enacted in 2001. (4) High-end products came to be produced stably in response to the latest demand for high-strength, high-workability, and high-toughness steels. (5) Environment conservation measures such as energy saving to reduce carbon dioxide emission and suppression of dust emission from plant buildings were taken while maintaining high productivity.

As a result of these efforts, four fundamental steel refining processes, namely desiliconization, desulfurization, dephosphorization, and decarburization, were separated from each other. Of these, the method of dephosphorization converged on the converter hot-metal dephosphorization process, which is excellent in thermal allowance and free from the use of fluorine. Varieties of secondary refining methods, aiming at securing sufficient degassing capacity for producing different kinds of steel and minimizing impurities and non-metallic inclusions, have been developed. These new technologies have made it possible to increase production while improving environmental protection measures. Historical developments of these new technologies are described below.

Table 1 outlines the historical changes of steel refining technologies over the last decades.

2.2 Separation of refining functions

2.2.1 Overview

By the 1980s, Nippon Steel Corporation established a separated refining process based on hot-metal pretreatment,[2] whereby the contents of silicon, sulfur, and phosphorus in hot metal were decreased before the decarburization in converters, using torpedo ladle cars, hot-metal ladles, or converters as the reaction vessels. Thereafter, technical developments such as the following were achieved:

* Department Manager, Steelmaking Technical Dept., Steelmaking Technical Div.
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071

Table 1 Themes of refining processes and the solutions

A.D.	Major event					Special mentions on the processes			
	Raw materials	Heat recovery	Production	Energy saving	Environment	De[S]	De[P]	De[C]	Secondly refining
							･Start up of LD−ORP (Nagoya)		
1990									
				･OG boiler (Kimitsu)			･Renewal of the control system (DDC)		
									･Start up of REDA (Yawata)
	･Start up of Scrap Melting Process (Hirohata)								
							･Start up of MURC process (Muroran)		
									･Mass production of IF steel
									･High speed decarburization
								･AC process in converter (Hirohata)	
	･Iron Reserve Barrel (IRB, Yawata)								
2000				･OG boiler (Oita)		･Desulfurization by injection in the ladle (Oita)			
					･Regulation of Fluorine in the soil	･Desulfurization by KR in the ladle (Kimitsu,Yawata)			
						･Separation of desulfurization process			
					･Reinforcement of converter dust collector		･Increase of converter type dephosphorization (Without Fluorine)		
	･Decrease of HMR		･Increase of converter working rate						･Additional LF (Muroran)
	･Scrap Melting in torpedo ladle		･Increase of converter heat size				･High speed operation of MURC process		
					･Converter without Fluorine			･High speed blowing in converter (nozzle improvement)	
	･Shredder machine (Nagoya, Oita)		･Shortening of converter cycle time						
		･Decrese of the heat conductivity of torpedo ladle refractory					･New dephosphorization furnace (Kimitsu)		
		･Increase of the torpedo ladle turn over					･New decarburization furnace (Nagoya)		･Additional RH (Nagoya,Kimitsu)
	･Dust recycle by RHF,DSP (Kimitsu,Hirohata,Hikari)			･Increase of LDG recovery		･New desulfurization furnace (Nagoya)			
2010			･Reinforced dust collection of plant buildings						･Increase of RH treatment (Oita,Kimitsu)
	･EAF for stainless steel (Yawata)						･Promotion of slag recycle		
							･All the hot metal dephosphorization		

separation of desulfurization from the other hot-metal pretreatment; separate processing of hot-metal dephosphorization from decarburization; development of hot-metal dephosphorization using converters as the reaction vessels and not requiring fluorine; improvement in reaction efficiency of these processes; recycled use of slag; adjustment of silicon content in hot metal in case of excessively high Si; and increase in converter capacity for hot-metal dephosphorization in converters.

2.2.2 Separation of hot-metal desulfurization

Hot-metal desulfurization used to be conducted simultaneously with dephosphorization or after it in the same reaction vessel. However, since desulfurization is a reducing reaction, its efficiency was low in the oxidizing atmosphere of dephosphorization, and in consideration of this, they were separated from each other to increase reaction efficiency. As for the method of desulfurization, injection of a CaO–Mg flux, excellent in desulfurizing ability, was developed,[3] and then, through modification of the KR process, a highly efficient method using a mechanical stirrer, a new process was developed at Yawata and Kimitsu Works.[4] Presently, either of these two processes is commercially practiced at the melt shops of the company in consideration of the production structures of each work.

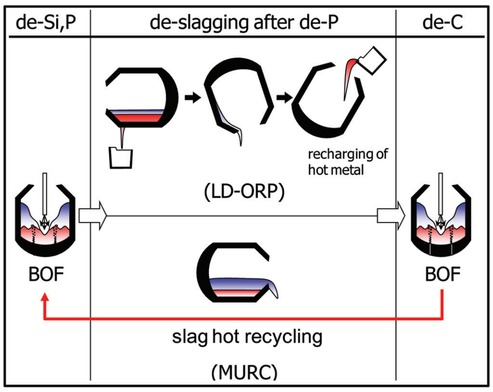
As a result of the process separation, it became possible to desulfurize hot metal at high temperatures in hot-metal ladles immediately after discharging from torpedo ladle cars, which improved reaction efficiency significantly. It also became possible to recycle the desulfurization slag to sintering plants; this has been actually practiced at some of the works.

2.2.3 Separation of hot-metal dephosphorization from decarburization

Hot-metal pretreatment in torpedo ladle cars or ladles enabled stable production of low-S, low-P steels, but decreased the thermal allowance for decarburization in converters, thus restricting the scrap ratio.[2] In consideration of this, new dephosphorization processes were developed on the basis of local production structures of different works, and commercially introduced widely in the company; in these processes, what was used as the reaction vessel was the converter, which has a large free board and is capable of dephosphorizing at high speeds under strong stirring effects of top-blown oxygen gas; the use of converters is also advantageous for increasing production because of the high scrap-melting ability.

As early as in 1989, using the then redundant converters of former No. 1 Steelmaking Plant, Nagoya Works developed the LD-optimized refining process (LD-ORP),[5, 6] and began to use it commercially. The process consisted of charging of hot metal into a converter designated exclusively for dephosphorization; removal of Si and P by blowing mainly oxygen gas, taking advantage of the large free board that torpedo ladle cars lacked; removal of S by bottom blowing of flux; deslagging; and transfer to a common converter for decarburization (**Fig. 1** [7]). Despite the trouble of the transfer from one converter to another, the process has been applied to increasing amount of hot metal in appreciation of low CaO consumption, high yield, and stable and high-speed operation of converters, and it was aimed to be applied to all hot metal.

After Nagoya, where it was developed, the LD-ORP process was introduced to Kimitsu and Yawata for the production of ultra-low-P



*LD-ORP(=LD converter - Optimized Refining Process)
*MURC(=Multi-Refining Converter)

Fig. 1 Converter type hot metal dephosphorization processes [7] steels. More recently, a modified process called ORP-II was commercially commissioned at Nagoya to further improve reaction efficiency, whereby hot metal is desulfurized in another converter vessel before dephosphorization. Although this modified method involves another change of vessels, it allows efficient desulfurization, dephosphorization, and decarburization by recycling decarburization slag for dephosphorization; in addition to low slag generation, this method consumes less amount of burnt lime.

Another method of separated dephosphorization and decarburization that the company developed is the multirefining converter (MURC) process, whereby the two processes are performed in the same converter vessel sequentially with deslagging in between.[8-10] The essence of this method is that P is removed efficiently under high oxygen potential, making use of the converter's strong stirring and oxygen blowing ability and low slag basicity (CaO/SiO_2). The slag formed during the decarburizing process is left in the vessel after tapping of steel, and used for the dephosphorization of a subsequent charge; this slag recycling minimizes heat loss and decreases slag formation (Fig. 1 [7]). However, since P and C were removed in the same converter vessel sequentially, the process cycle time tended to be long, and it was necessary to shorten it for the method's commercial application. Now, the cycle time has been shortened to 35 - 37 min. This method proved effective at producing ordinary carbon steels (except for ultra-low-P steels) very efficiently in aspects such as CaO consumption, slag formation, and thermal allowance, and for this reason, after it was developed at Muroran, commercially introduced to Oita, Kimitsu, Yawata, and other works.

In the 2000s, fluorine use was restricted as part of the environmental quality standards for soil, and the development of dephosphorization processes not using fluorine was promoted. To remove P from hot metal in conventional small reaction vessels such as torpedo ladle cars and hot-metal ladles, it was necessary to decrease the slag formation to prevent overflow, and in this situation, use of fluorine was necessary to raise the slag basicity; the process efficiency fell markedly without it. As a solution, the hot-metal dephosphorization methods using converters became widely practiced, since the large inner volume of converters allowed the use of a large amount of low-basicity molten slag without fluorine.

As stated above, hot-metal pretreatment methods taking advantage of converters showed rapid advances since the 1990s, and as a result, the shares of the LD-ORP and MURC processes in hot-metal dephosphorization increased, replacing conventional processes using torpedo ladle cars or hot-metal ladles, as seen in **Fig. 2**. As of the beginning of 2012, the converter dephosphorization methods are responsible for about 95% of the hot-metal dephosphorization of the company; our plan is to make the Figure reach 100% in 2013.

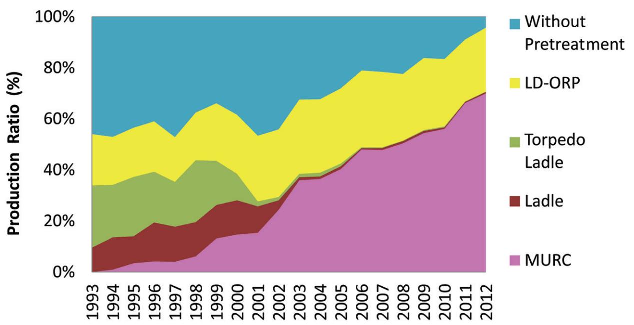


Fig. 2 Shares of different methods of hot-metal dephosphorization

2.2.4 Desiliconization of hot metal

Increase in the silicon content of hot metal from blast furnaces leads to an increase in CaO consumption and a consequent increase in slag formation in steel refining. As far as dephosphorization was conducted in torpedo ladle cars or hot-metal ladles, it was necessary to decrease slag formation because of the limited vessel volume, and hot-metal silicon had to be minimized beforehand, and after discharging the desiliconization slag, hot metal was dephosphorized with high-basicity, high-melting-point slag containing F.[11] In contrast, by converter-type dephosphorization, it is possible to remove P and Si by oxygen blowing using the slag of comparatively low basicity and low melting point, without F, taking advantage of the large volume of the vessels. This means that it is not necessary to minimize the Si content of hot metal, but there is a Si content level most suitable for dephosphorization. The standard practice in the company presently is to desiliconize before dephosphorization only when the hot metal contains Si in excess of the most suitable level. However, the desiliconization capacity of the company is insufficient, and it is desirable to expand it so as to decrease the discharge of steelmaking slag and improve molten steel yield.

As stated above, Nippon Steel Corporation has enhanced the reaction efficiencies of the four fundamental steel refining processes, namely desiliconization, desulfurization, dephosphorization, and decarburization, by separating them from each other, and reduced costs and slag discharge by separately recovering and recycling the slag arising from these processes. The steelworks of the company have restructured their refining facilities into the states shown in **Fig. 3**, making the most of their respective production structures.

2.2.5 Promotion of slag recycling and reduction of slag discharge

The slag from decarburizing reactions is of a comparatively high basicity, but because it is left in the converter under the end-point condition at high temperatures, its phosphoric acid concentration is low. For this reason, its reuse for hot-metal dephosphorization at lower temperatures is advantageous for decreasing CaO consumption and cost reduction. In view of this, decarburization slag is recovered without mixing with others and recycled for dephosphorization. By the MURC process, it is possible to recycle slag by letting it solidify in the converter after steel tapping and using it for the hot-metal dephosphorization of the following charge; this is actually

Works	Separation of the 4 refining processes			
	De[Si]	De[S]	De[P]	De[C]
Yawata	Torpedo	⇒ Ladle KR Injection	⇒ Converter MURC Partially Torpedo	⇒ Converter
Muroran	Torpedo	⇒ Torpedo (De[S] in LF)	⇒ Converter LD−ORP MURC	⇒ Converter
Nagoya	Converter (Partially)	⇒ Converter Desulfurization Furnace	⇒ Converter LD−ORP	⇒ Converter
Kimitsu	Torpedo	⇒ Ladle KR Partially Torpedo	⇒ Converter LD−ORP MURC	⇒ Converter
Oita	Torpedo	⇒ Ladle Injection	⇒ Converter MURC Partially Ladle	⇒ Converter

Fig. 3 Separation of refining processes in NSC

practiced at many works. In addition, there is a plan to recycle decarburization slag to the sintering process when too much of it is formed, but this is possible only when dephosphorization and decarburization of hot metal are separate from each other. Thus, the company has successfully decreased slag discharged to the outside by increasing the ratio of hot-metal dephosphorization and consequent recycling of decarburization slag and the preliminary removal of excessive Si in hot metal.

2.2.6 Promoting refining reaction analysis using numerical models

In addition to the removal of S, P, and C, oxidation and reduction of Si, Mn and Fe occur in parallel in the steel refining process, and many mathematical models have been developed and applied to analyze and optimally control those reactions. On the basis of competitive reaction models,[12)] Nippon Steel Corporation has developed a set of comprehensive reaction analysis models, called the mathematical analysis codes for slag-metal reaction and injection metallurgy (MACSIM),[13)] and used it for operation analysis. In dephosphorizing reactions, on the other hand, considering the fact that the distribution of P between the solid and liquid phases of slag is influenced by the iron oxide concentration in slag,[14)] the Iron & Steel Institute of Japan (ISIJ) formulated a multiphase calculation model for estimating the mass transfer among the solid, liquid, and metal phases of slag on the basis of competitive reaction models.[15, 16)] In the present operation of LD-ORP, removal of P has been improved by increasing the iron oxide concentration in slag at the middle of the dephosphorizing stage so that P concentrates in the solid phase, following the result of the multiphase slag analysis.

On the other hand, jointly with IRSID, Nippon Steel Corporation's Advanced Technology Research Laboratories developed thermodynamic models for calculating the state of equilibrium at the end of refining reactions.[17, 18)] Multipurpose thermodynamic models based on a cell model and making use of the huge accumulation of thermodynamic database are available now, which proved instrumental in the field research and development activities. On the other hand, further development to enhance estimation accuracy is awaited with respect to databases on some element systems.

Lately, it is possible to accurately predict heat and mass transfer in a variety of processes. Analysis by simulation based on numerical calculation is widely applied to development studies as well as plant operation. As seen with examples given later herein, sufficiently high accuracy has been obtained in the analysis of the top-blown oxygen jet of converters and the numerical calculation of the dust emission during charging of hot metal into a converter and the atmospheric dust contents on the operators' floor thereafter.

2.3 Production increase and cost reduction

2.3.1 Background

After the turn of the century, aiming at increasing production while maintaining the hot-metal pretreatment ratio at a high level, Nippon Steel Corporation's steelmaking plants focused on the increase in the production capacity of converters, improvement in flexibility in the choice of feed stock, and decrease in the hot-metal ratio (HMR) by increasing thermal allowance. One of the reasons was that it became necessary to dephosphorize hot metal using converters because of the said restriction on the use of fluorine. As a result, it became possible to enjoy greater thermal allowance that the converter-type hot-metal pretreatment offered, which enabled to dephosphorize hot metal while lowering HMR to increase the use of scrap. However, this decreased the production capacity of converters because dephosphorization took the process time of converters. To solve the problem, it was necessary to review the production capacity of converters radically.

2.3.2 Increase in converter production capacity

There are three means to increase the production capacity of converters: increasing the heat size, raising the working ratio, and shortening the cycle time. All of these were pursued, and as a result, an annual production of 33 million tons was attained without having to construct a new converter shop; HMR at that time was roughly 80% (**Fig. 4**). After Lehman's fall, while the steel production recovered to somewhere near the level before it, the ratio of hot-metal dephosphorization was increased to about 95% and maintained at that level (Fig. 2).

The heat size was increased by increasing the vessel volumes and crane capacities at the time of their renewal and by enlarging ladles at the time when the economic conditions allowed production increase.

As for the working ratio, introduction of flame spraying and gunning facilities for refractory maintenance and for splash coating proved effective in shortening the repair time. In addition, special equipment for quick tap-hole repair was introduced to shorten the repair time of tap-hole refractory, and special lances for removing skull from the vessel nose were provided.

On the other hand, to shorten the cycle time, the nozzle diameter of the oxygen blowing lance was enlarged and the blowing angle was widened to shorten the blowing time.

As a consequence to the increase in the ratio of hot-metal pretreatment, decarburizing became the main role of converters, and over the last years, the focus in the development of converter operation technology has shifted to high-speed processing to raise productivity. In this situation, the large-diameter, wide-angled lance nozzle design was instrumental in increasing the oxygen blowing speed and shortening the processing time together with slopping sensors and converter gas analyzers. This led to reacknowledgement of the importance of lance nozzle design and the blowing patterns (blowing speed, lance height, etc.) for shortening the converter cycle time.

Suppressing dust emission is important, especially as a countermeasure against yield decrease due to high-speed blowing. A lance tip design was developed to control the flow of the oxygen jet in consideration of the expanding characteristics of the ultrasonic gas jet.[19, 20)] Numerical calculation technology, which has advanced remarkably, greatly contributed to the lance tip design by accurately predicting the combined behavior of gas jets from many nozzles, which affects the jet flow characteristics (**Fig. 5**).

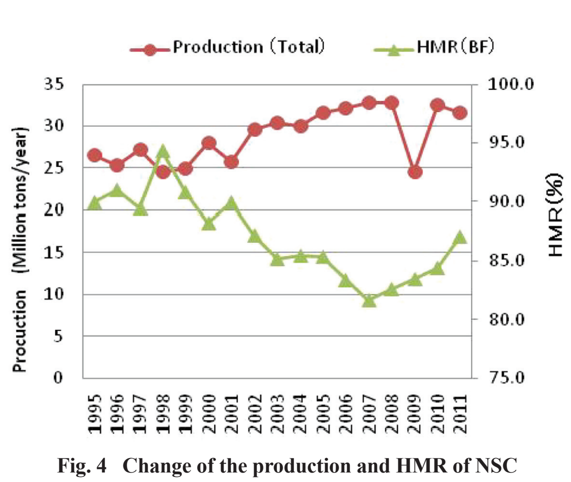


Fig. 4 Change of the production and HMR of NSC

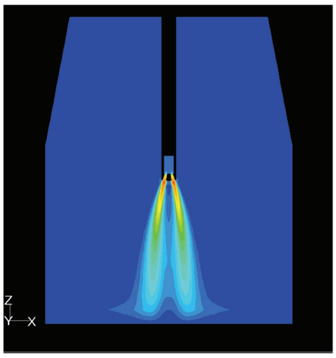


Fig. 5 Example of the calculation result of top blown jet

2.3.3 Advance in converter refining technology

(1) Stirring of Steel Bath by Bottom Blowing in Converters

Three different methods of converter bottom blowing were developed by the end of the 1980s and commercially introduced to all works of the company according to their characteristics[1]: LD-oxygen bottom blowing (LD-OB), whereby part of the top-blown oxygen is blown in from the bottom; LD-CO_2 bottom bubbling (LD-CB), whereby inert gas is blown in from the bottom; and LD-powder bottom blowing (LD-PB), whereby lime stone powder is blown in. LD-OB was introduced at Yawata, Nagoya, Kimitsu (No. 2 Steelmaking Plant), and Oita in appreciation of its ability to strongly stir the steel bath, and LD-CB at Kimitsu (No. 1 Steelmaking Plant) and Muroran, where, because of product mix, it was necessary to decrease the bottom-blown oxygen during the refining process to obtain high end-point carbon. LD-CB was also used at Hirohata for the decarburizing furnace coupled with the scrap melting process (SMP), which is explained later herein. LD-PB, advantageous for dephosphorization, was employed at Nagoya's ORP converters.[2]

The amount of bottom-blown oxygen by LD-OB is from 0.15 to 0.20 Nm^3/t/min at present; if the blowing amount is increased further, the decrease in iron oxide content in slag will be limited. Bottom blowing nozzles last long enough to sustain a vessel campaign without nozzle change.

(2) Intensive Use of Sensors for Accurate Blowing Control

Nippon Steel Corporation has developed sensor technologies to obtain information on the conditions inside converter vessels for higher process control accuracy. Microwave level gauges were introduced to detect the molten metal level after the charging. This made it possible to quickly determine the lance–metal distance without having to use sub-lances, and improved the accuracy of the blowing operation.

Another type of sensor capable of detecting acoustic pressure was introduced to detect the level of slag surface. The sensor has made it possible to know the time when slag hides the lance jet, by measuring the fall of sound pressure.

Laser profile meters are used for detecting the wear of refractory lining, and it became possible to know the local refractory wear quickly and more frequently to raise the efficiency of furnace maintenance.

The advances in these sensor technologies have proved greatly instrumental in stabilizing the operation and refractory control of converters and minimizing operation troubles. Together with the effect of 100% dephosphorization of hot metal to stabilize the converter blowing process, advanced sensor technologies have enabled one-sub-lance operation, whereby once blowing starts on the basis of the temperature measurement and determination of starting chemistry using a sub-lance, it ends following the dynamic process control, and the steel is tapped without further temperature measurement and sampling by inserting a second sub-lance.[21]

2.4 Increases in flexibility of feed-stock selection and thermal allowance

2.4.1 Increased use of economical scrap

In the early 2000s, to increase steel production, steelmaking furnaces were required to decrease HMR in view of the limited pig-iron production capacity. This made it necessary to increase the flexibility in the selection of metal sources, and thus increase thermal allowance. Since higher flexibility in the selection of metal sources meant increased use of economical scrap from the market, measures to remove impurities and increase the bulk density were introduced for increased use of low-grade scrap.

Shredders were built to separate impurities, and presses to increase bulk density. Through shredding, combustibles were removed and the dust emission at scrap charging into converters was also decreased.

2.4.2 Increase in thermal allowance and more use of scrap

To increase thermal flexibility, measures were taken to raise the turnover rate (the number of hot metal received per day) of torpedo ladle cars and melt cold scrap iron in them.

Raising the turnover rate is effective at decreasing radiation heat loss, and for this purpose, the number of torpedo ladle cars in daily operation was cut down; as a result, the turnover rate now exceeds three at most of the company's works. Melting of cold scrap in torpedo ladle cars was made commercially practicable at Oita, largely contributing to increasing thermal allowance. The method consists of charging scrap arising from inside the works into empty torpedo ladle cars after discharging hot metal, and then receiving hot metal from a blast furnace; the practice is effective at decreasing the amount of the radiation heat of empty torpedo ladle cars lost to air. In commercial production, scrap corresponding to 1.5% of steel output was charged into torpedo ladle cars, and a decrease in heat loss equivalent to hot-metal temperature of approximately 8°C was realized.

In addition, the radiation heat loss of torpedo ladle cars was decreased by changing their lining refractory to a low-heat-conductivity type in order to lower the steel shell temperature: in fact, the radiation heat loss was decreased by about 10°C in terms of hot-metal temperature by lowering the thermal conductivity of the wear bricks from 19 to 8 W/m/K.

An iron reserve barrel (IRB) equipped with an induction heater was installed at Yawata Works in 1998 to melt scrap to supplement the thermal allowance of the converter operation; the IRB heater exhibited an iron meting capacity of approximately 60 t/h.[22]

After the blow-off of the blast furnace in 1993, Hirohata Works developed SMP,[23] whereby scrap iron from inside the works and the market is melted in a special melting furnace, and the molten metal is refined into steel by using conventional converters, and began commercial steel production by the process. The SMP was then combined with the system of rotary hearth furnaces (RHFs) to produce directly reduced iron (DRI) from metal-containing dust arising from inside steel works (see 2.4.3 below). The dust recycling through the RHFs and SMP has proved advantageous and the recycling amount has increased ever since.

The molten metal from the SMP turns into steel through desulfurization in hot-metal ladles, top blowing in common basic oxygen converters, and secondary refining in the RH degasser or composi-

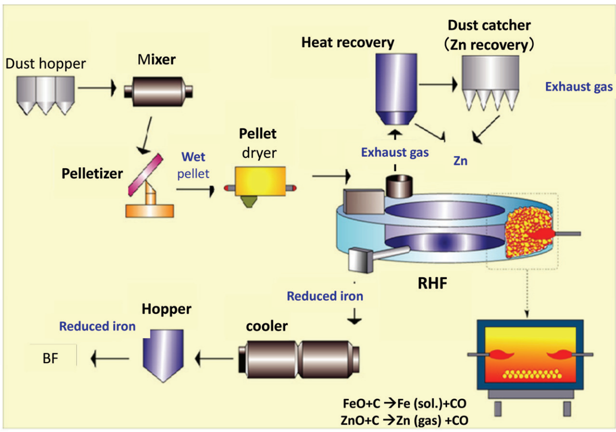


Fig. 6 Example of RHF process flow (Kimitsu)

tion adjustment by sealed argon bubbling (CAS) facilities. Because the molten metal from the SMP does not contain Si, fine powder of burnt lime is injected through the top-blowing oxygen lance to increase the efficiency of dephosphorization in the converter;[24] this process is called the Arbed-CNRM (AC) process.

2.4.3 Promotion of dust recycling

Nippon Steel Corporation has developed dust recycling processes and expanded their actual use. Dust reducing systems using RHFs have been commercially operated at Kimitsu, Hirohata, and Hikari Works. (Hikari Works was reorganized in 2003 as a work of Nippon Steel & Sumikin Stainless Steel Corporation.) The system in Kimitsu has three RHFs to reduce dust arising from inside the works and to remove zinc from it, and the product DRI is fed to the blast furnaces (**Fig. 6**). The system in Hirohata has four RHFs to reduce dust and remove zinc into DRI, part of which is then formed into hot briquetted iron (HBI); these recycled products are turned into molten pig iron either through the SMP or the DRI smelting process (DSP). Hirohata's system recycles dust from inside the works as well as from outside sources into easily usable metallic iron in small lumps. The RHF system in Hikari recycles dust from stainless steel production processes into materials for electric arc furnaces.

2.5 Enhancement of secondary refining functions

2.5.1 Wider application of degassing

Dehydrogenation treatment has long been applied to molten steel for plate products. More recently, as the cold-rolled steel sheets for automotive use came to be produced through continuous annealing, production of steels requiring decarburizing, such as interstitial-free (IF) steel, increased markedly. As automotive sheets became wider and the casting speed of continuous casters increased, it became necessary to shorten the process time of secondary refining, and measures to accelerate decarburizing reactions advanced. Various elementary measures were taken to shorten the process time of RH degassing, such as increase in diameter of the snorkels, increased flow of circulating gas, and capacity increase of vacuum exhaust systems. A method widely used for attaining vacuum quickly at the beginning of the processing is the preparatory vacuum method, whereby the vacuum exhaust system is severed from the processing tank and kept exhausted before the processing.[25] The efficiency of vacuum exhaust systems was improved through introduction of high-performance boosters and ejectors. RH degassers equipped with vacuum exhaust systems combined with high-efficiency mechanical pumps were installed at Nagoya (No. 3 RH) in 2007 and Kimitsu (No. 3 RH) in 2010.[26]

Because of these measures and new facilities, the process time of RH decreased significantly, enabling production of IF steels in large quantities. Addition of RH facilities improved the operation synchronization with continuous casting, and as a consequence, carbon contamination was decreased by sequential treatment of ultra-low-C steels using the same RH degasser. In addition, to estimate the ending time of decarburization by calculation and to reduce the process time, various decarburization models were worked out and applied to actual operation.[27]

Nippon Steel Corporation's RH degassers are equipped with multifunction burners (MFBs) for top-blowing oxygen for decarburizing and heating during treatment and keeping the vacuum tank hot. The MFB can blow fuel together with oxygen through a lance inserted in the treatment tank to keep it hot either during the vacuum processing or at the atmospheric pressure, and heat steel by blowing oxygen and burning aluminum. Keeping the tank hot is effective at decreasing the scull formation inside it, which helps shorten the process time of ultra-low-C steels and allows converters to lower the end-point temperature.[28, 29]

The revolutionary degassing activator (REDA) was developed through modification of the DH degasser to increase the treatment efficiency beyond that increased by the periodical processing of the original DH. By this method, which uses a single snorkel as DH, degassing advances efficiently through slag–metal reactions inside the snorkel, assisted by stirring of the steel by bubbling of the inert gas from the ladle bottom; the DH degassers of Yawata and Kimitsu were modified into REDA by 1997 (**Fig. 7**).[30] The treatment amount of degassing has increased steadily, as seen in the graph. With increasing production of steels requiring degassing, degassers came to be used continuously to prevent the equipment from cooling, which decreased refractory costs and allowed lower end-point temperature of converters. In appreciation of these advantages, light RH treatment is applied to increasing amount of ordinary carbon steel. Actually, at Oita and Kimitsu, where the RH facilities are capable of treating the entire steel from the converters, the entire steel undergoes normal or light RH treatment.

2.5.2 CAS-OB

The composition adjustment by the sealed argon bubbling-oxygen blowing (CAS-OB) process is a simplified secondary refining process to be applied immediately after tapping from converters, and is widely applied to steels not requiring degassing. It was initially meant to replace the conventional deoxidizing and composition adjustment treatment using bottom bubbling in ladles. Lately, however, as the application of the light RH treatment increased, as mentioned above, the treatment share of CAS-OB is decreasing.

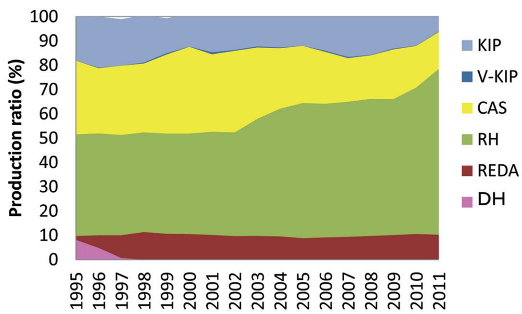


Fig. 7 Shares of secondary refining processes

2.5.3 Expansion of LF capacity

To shorten the process time of secondary refining, Nippon Steel Corporation avoids the use of ladle furnaces (LFs) for ordinary steels, but their use is limited to those of ultra-low oxygen contents and those requiring heating after tapping, namely the ones for bars and wire rods, special steels for heavy plates and high-C steels. To minimize inclusions in special steels, Muroran's Steelmaking Plant installed a second unit of LF so that all the steel could undergo LF treatment.

2.5.4 Stable production of high-purity steel

In response to increasing demand for high-end products such as ultra-low-P, low-S, sower-resistant pipes; low-S, high-strength thin sheets; and low-P, low-S heavy plates, Nippon Steel Corporation has developed technologies for producing high-purity steels in large quantities.

Hot-metal dephosphorization using converters (such as LD-ORP), torpedo ladle cars, or hot-metal ladles is effective at stable production of ultra-low-P steels; a P content of 54 ppm or less is achievable.

Ultra-low-S steels are produced stably by using the RH injection method,[31] whereby desulfurizing flux in powder is injected into steel during RH degassing or the Kimitsu injection process (KIP), whereby the flux injection is done in a ladle. The KIP used to be employed for desulfurization and other processing of a wide variety of steels not requiring degassing, but it is being replaced by the light RH treatment, as stated before.

By the RH injection method, originally developed at Oita Works, desulfurizing flux is injected through a J-shaped refractory lance into molten steel in the up-flow snorkel of an RH degasser so that degassing and desulfurization are performed at one place. KIP, on the other hand, involves blowing flux into molten steel in a ladle thorough a refractory lance. The process and its modification, called V-KIP,[32] whereby the process goes in a vacuum tank, both developed at Kimitsu, enable stable production of low-S steels; a sulfur content of 7 ppm or less is attainable. These multifunction secondary refining processes were industrially established by the 1990s.[1]

While the ISIJ has watched the historical change in the upper-limit specification figures of impurity contents including P and S at an interval of 10 years,[33] the steelmakers of Japan have established their own production processes of low-P and low-S steels by the 1990s.

2.5.5 Development of stainless steel production technology

Nippon Steel Corporation used to smelt stainless steel at Yawata and Muroran Works by adding ferrochromium to hot metal in converters, and then decarburizing the metal under oxygen blowing, followed by degassing. After the closure of the hot strip mill of Muroran in 1987, smelting of stainless steel was concentrated at Yawata. At the beginning, Yawata employed the vacuum oxygen decarburization (VOD) process for final decarburization, but after the REDA was developed, the new process was used for decarburizing stainless steel in appreciation of high degassing efficiency and low nitrogen adsorption.[34]

Later, an electric arc furnace was commissioned for stainless steel production at Yawata in 2010. This was for melting ferrochromium and stainless steel scrap into molten steel, which would then be mixed with hot metal from blast furnaces and decarburized in converters. This process route enabled the use of economical ferrochromium and scrap arising from inside the works.

2.6 Automation and labor saving

The operation control facilities and systems of Nippon Steel Corporation's steelmaking plants that had worked since they started up in the 1970s aged in the 1990s, and control facilities incorporating the then latest direct digital control (DDC) function were introduced on the opportunity of their renewal. Here, special attention was paid to the points such as the following: (i) automatic processing by linking control devices to process computers; (ii) improvement in labor efficiency and communication by unification of control rooms and operating tables; (iii) preparation of infrastructure for training and fostering of multirole or all-round workers; and (iv) formation of operation information database, which enables easy analysis.

As a result, the operators' rooms of hot-metal pretreatment, converter operation, and secondary refining were centralized in each of these areas at different works of the company. Presently, a converter is basically operated by a team of three people per shift, and secondary refining processes are operated by one person per process per shift.[35]

2.7 Measures for energy saving ad environmental protection

2.7.1 Measures for energy saving

Energy saving was tackled and efforts were bent to increase the steam generation and LD gas recovery to cut energy costs and CO_2 emission. Boilers were added to the oxygen converter gas recovery (OG) systems often taking the opportunity of the renewal of their hoods,[36] and as a result, the steam recovery rate has exceeded 80 kg/t-steel at most of the works. The recovery amount of LD gas has increased because of shortening of the analysis time of the gas from converters and starting gas recovery earlier in a converter operation cycle than before.

2.7.2 Measures to suppress dust emission from plant buildings

Measures were taken to suppress dust emission from the plant buildings during the period of production increase, when HMR was lowered and the scrap ratio was increased. Dust arises during the charging of hot metal into converters; the primary dust collection by the OG system and local dust suction at the converter nose were sometimes insufficient, leading to dust emission to outside the plant building. Dust collection of the entire building was studied as a countermeasure. The capacity of the suction fan was determined through simulation of the flow of gas and dust inside the plant building in question and calculation of the blower capacity required for collecting dust from the converter nose and the building. After the start-up, the dust concentration prediction by calculation proved to be in good agreement with actual results. The method of simulation and calculation of the wind volume was applied to the design of other dust collectors as well.[37, 38]

3. Future Prospects

3.1 Further cost reduction

Our continued tasks include reduction of the refining costs of high-end steels and ordinary steels. Judging from the efficiency of lime stone in desulfurization and dephosphorization reactions, there is still much room for improvement of refining operations, especially in relation to slag recycling and reaction efficiency. Further efforts will be focused on these two subjects. Here, effective application of various calculation methods that have been developed for different objectives will be important. Sensing technology offers the means for collecting information on reactions in furnaces and vessels, and supplies reliable bases for calculation of reaction processes during operation. There is much room for more effective application of this technology.

3.2 Measures for environmental protection

Nippon Steel Corporation will continue pursuing further energy saving, eliminating fluorine use and minimizing slag discharge to outside. Regarding the decrease in slag discharge, emphasis is placed on further expansion of reuse of slag inside steel works as well as reduction of the costs for hot-metal desulfurization and dephosphorization.

4. Closing

Solutions have been worked out and significant advances accomplished regarding the targets set forth in our report 18 years ago, namely optimum division of steel refining functions, increase in the flexibility in the selection of feed stock, and environmental harmony. In the next couple of decades, the company will have to respond to more changes in business environment and further expand the overseas ventures that it has embarked upon. We have to continue improving our technical capability that has been fostered to cope with such changes and challenges.

References

1) Endoh, K.: Shinnittetsu Giho. (351), 3 (1994)
2) Kitamura, S. et al.: Tetsu-to-Hagané. 6, 1801 (1990)
3) Washizu, S. et al.: CAMP-ISIJ. 15, 876 (2002)
4) Shin, K. et al.: CAMP-ISIJ. 13, 867 (2000), for example
5) Katoh, I. et al.: CAMP-ISIJ. 4, 1153 (1991), for example
6) Mukawa, S. et al.: Tetsu-to-Hagané. 80, 25 (1994)
7) Iwasaki, M. et al.: Shinnittetsu Giho. (391), 88 (2011)
8) Hayashi, H. et al.: CAMP-ISIJ. 15, 139 (2002)
9) Kumé, K. et al.: CAMP-ISIJ. 16, 116 (2003)
10) Ogawa, Y. et al.: Tetsu-to-Hagané. 87, 21 (2001)
11) Yonezawa, K.: Report on the Activity of Minimization of Steel-making Slag. ISIJ, 1999, p. 50
12) Ohguchi, S. et al.: Ironmaking Steelmaking. 11, 202 (1984)
13) Kitamura, S. et al.: CAMP-ISIJ. 4, 202 (1991), for example
14) Itoh, K. et al.: Tetsu-to-Hagané. 68, 342 (1982)
15) Kitamura, S. et al.: Tetsu-to-Hagané. 95, 127 (2009)
16) Miyamoto, K. et al.: Tetsu-to-Hagané. 95, 13 (2009)
17) Yamada, W. et al.: Shinnittetsu Giho. (342), 38 (1991)
18) Yamada, W. et al.: CAMP-ISIJ. 8, 792 (1995)
19) Naitoh, K. et al.: CAMP-ISIJ. 11, 146 (1998)
20) Naitoh, K. et al.: CAMP-ISIJ. 10, 168 (1997)
21) Fukuda, Y. et al.: CAMP-ISIJ. 7, 1121 (1994)
22) Takahashi, Y. et al.: CAMP-ISIJ. 13, 48 (2000)
23) Ohnuki, K. et al.: CAMP-ISIJ. 6, 1028 (1993)
24) Nagai, W. et al.: CAMP-ISIJ. 13, 89 (2000)
25) Kunitake, O. et al.: CAMP-ISIJ. 7, 216 (1994)
26) Higashi, T. et al.: CAMP-ISIJ. 24, 165 (2011)
27) Kitamura, S. et al.: Tetsu-to-Hagané. 80, 31 (1994)
28) Ohnuki, K. et al.: CAMP-ISIJ. 7, 240 (1994)
29) Yano, M. et al.: Shinnittetsu Giho. (351), 15 (1994)
30) Okimori, M. et al.: Shinnittetsu Giho. (374), 47 (2011)
31) Endoh, K. et al.: Seitetsu Kenkyu. (335), 20 (1989)
32) Kuwashima, S. et al.: Tetsu-to-Hagané. 72, S250 (1986)
33) Sasabe, M.: Ferrum (Bulletin of ISIJ). 15, 562 (2010)
34) Miyamoto, K. et al.: CAMP-ISIJ. 12, 748 (1999)
35) Mori, K. et al.: CAMP-ISIJ. 12, 739 (1999), for example
36) Morioka, M. et al.: CAMP-ISIJ. 5, 219 (1992)
37) Mimura, Y. et al.: Shinnittetsu Giho. (394), 75 (2012)
38) Kawahito, K. et al.: Shinnittetsu Giho. (391), 122 (2011)

Masanori KUMAKURA
Department Manager
Steelmaking Technical Dept.
Steelmaking Technical Div.
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071