Stirring in the Steelmaking Processes*

By Takeshi KATO**

I. Opening Remarks

It is indeed a great honor for me to be awarded with the G. Watanabe Medal, for which I sincerely thank you all.

When I was asked to deliver a memorial lecture, however, I was at a loss as to what to talk about in an orderly manner, because it has been already some 24 years since I left the field of research and devoted myself to jobs somewhat sundry. After some pondering, I came upon a theme of "Stirring in the Steelmaking Processes," a subject which I have been interested in through all these years.

That is to say, in the evolution of the steelmaking process, it seems to me that the "stirring" to achieve the desired states of chemical composition and temperature most efficiently with regard to the quantity and time available has been occupying a very important position. I wish, therefore, to review this evolution of steelmaking methods with "stirring" as my viewpoint.

II. Changes of Stirring in the Steelmaking Processes

I have illustrated in Fig. 1 the evolution of steelmaking as viewed from the methods of stirring applied to various processes. You will note that even in the past the first process of obtaining steel from hot metal, the puddle method, stirring was undertaken just as its name implied. As decarburization proceeded, however, the melting point of hot metal raised, aggravating its fluidity, and puddling with firewood became necessary. This stirring by human power had been used in the open hearth furnaces and electric arc furnaces of the later age until methods of stirring by gas were implemented.

When the Bessemer converter made its appearance, intensive stirring by bottom-blown air became a new refining means, thereby replacing the puddling. Due to this strong stirring action, decarburization and temperature raising became easy, which made steelmaking much easier.

With the open hearth furnace, which subsequently became the mainstream of steelmaking, the stirring technology became important again to prevent over-oxidation of molten steel and to augment heat conduction. Here, besides the traditional puddling or similar methods, the throwing-in of ingot pig or lime stone, so-called lime boiling, were added as new stirring methods. As mass production of oxygen

was established, the blowing of pure oxygen, called the bessemerizing, was perfected; this gave rise to effective stirring, which made the operation of open hearth furnace easier and more efficient and greatly raised productivity.

Yet, the demand on the ingenuity of engineers was quite heavy: for example, in the making of Armco iron or ingot iron in an open hearth furnace, because the steel bath was apt to become excessively hotter in the upper layer, as decarburization proceeded and steel became inactive, all sorts of stirring, including manual stirring with a stange (pole or rod), the throwing-in of pig irons, and blowing-in of oxygen, had to be tried. Table 1, which I found in the 1962 edition of our *Iron and Steel Handbook*, tells you its own story.

Though methods of stirring similar to those for open hearth furnaces were employed for electric arc furnaces, adaption of an electromagnetic stirrer to the furnace bottom became popular with large furnaces to make the slagging-off after oxidation refining and the subsequent reduction refining easier. And this method evolved later into the ASEA-SKF secondary refining process or into the electromagnetic stirring in the continuous casting.

Then came the LD converter. As we started production, we became aware of an acute need for understanding the slopping phenomenon and solving it. The simulation studies on the dynamic behavior of the steel bath under an oxygen jet by means of water models, gave us the following insight that by taking, contrary to the generally accepted idea, the L/L_0 ratio large, namely, by making the oxygen jet crater deeper relative to the steel bath depth, slopping can be prevented.

In the meantime, studies of dephosphorization were energetically undertaken for converters of high hot metal ratios, because [P] was apt to become high unless low [P] metals were discriminately provided.

Prevention of slopping and dephosphorization are mutually contradicting propositions, and how to satisfy both has been a great concern of steelmaking engineers. Notions like the hard blow or the soft blow were advanced, but in actual operations, it was the control of lance clearance in consideration of the blowing time, the kind of steel to be made, the life of furnace, and such, that proved most effective.

When enlargement of the LD converter began to be studied, the question was, if one and single lance

* Based on the Special Lecture delivered by Dr. Kato on the commemoration of his receiving G. Watanabe Medal in the 111th ISIJ Meeting on April 2, 1986, at The University of Tokyo in Tokyo. Manuscript received on May 23, 1986. © ISIJ 1986

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Fig. 1. Changes in the method of steelmaking and stirring.

Table 1. An example of making Armco iron in a 60 t open hearth furnace.

Time (hr)	1°		2°		3°	
C	1.28	0.25	0.07	0.05	0.039	0.020
Mn	0.15	0.06	0.06	0.04	0.04	0.038
(%) P	0.020	0.010	0.010	—	—	—
S	0.027	0.019	0.019	0.016	0.016	0.015
Σ FeO						40.5
Remarks	Ore 3 t	Lime 1 000 kg	Ingot pig 300 kg		Al pig 100 kg	
	Ore 300 kg O ₂ blow 18'	Stirring with stange (rod)	Stirring with stange (rod)		O ₂ blow 7'	Tapping O ₂ blow 7'15''

Source: Iron and Steel Handbook, ed. by ISIJ, Maruzen, Tokyo, (1962), 369 (in Japanese).

would be enough for adequate mixing. Simulation studies with water models gave us an answer through dimensional analysis in the affirmative. But I remember I jokingly asked that if we set up just one big

lance at the dead center of the Tokyo Bay, do we get a good mixing in Ghiba and Kawasaki? So, we thought a large scale experiment should be made in order to make a feasibility study of large converters,

* Two cities that face each other diametrically across the Tokyo Bay, and that are well known for their great integral steelmaking plants.

and we made a large plastic model. To visualize the states of mixing at periphery, we hang, of all things, china marble candies along the wall, because they change color as they melt.

This experiment made us suspect that the stirring in the periphery would be insufficient, whereupon we decided on two courses of research. In one, we conducted experiments of tangential bottom-blowing of inert gas in a small experimental furnace, while in the other, we pushed forward with the development of a multiple-nozzle lance. We found soon enough that, as the use of a multi-nozzle lance gave rise to good mixing in the steel bath even with soft blow, slopping was prevented, and operation much stabilized. Thus, implementation of the multi-nozzle lance made enlargement of LD converter possible with one lance, which in turn made the converter steelmaking progress by leaps and bounds. As one reason why the converter steelmaking technology made such remarkable progress here in Japan, I would like to cite the efforts all of us expended in earlier times in controlling the flow in the steel bath due to oxygen jet.

As for the inert gas bottom-blowing experiment that I mentioned, we had to discontinue it even though we did plan on a larger-scale experimentation, because we did so well with the multi-nozzle lance on one hand and we decided to use that experimental converter for the study of converter gas recovery, on the other hand. We did not know then that we were to revive this technology 17 or 18 years later to augment the stirring, which was thought still insufficient for large converters.

III. Top and Bottom Blowing Converter

In Europe, where high phosphorus ores were used, the Thomas converter was popular, but as oxygen became widely available, studies of the so-called

improved Thomas process, which utilizes oxygen enrichment of the bottom-blown air, was intensively pursued. In this method, steam of CO_2 was also used to protect the tuyere, and in an extension of this, the double-tube tuyere was developed. From this, furthermore, methods of using fuel as well as pure oxygen to protect the tuyere were developed, making it possible to blow in oxygen from the bottom, namely giving birth to the bottom blowing oxygen converter.

To give theoretical foundation to the features of the bottom blowing oxygen converter of quiet and steady progress of reactions, yet with little formation of (FeO) , re-examination of stirring was begun. It was found that, when stirring was augmented by bottom blowing, merits such as (1) decreased oxidation losses of Fe and Mn in the low carbon range and (2) improved controllability due to the elimination of inhomogeneities in composition and temperature of the steel bath was readily be enjoyed. Also, attempts at quantification of the effects of stirring were made.

In those studies, a notion that for LD converters the stirring by oxygen jets alone is insufficient has been put forward. As a difficulty of slag control was apparent with bottom blowing oxygen converters, however, development of the top and bottom blowing converter that takes advantage of the merits of both was pursued intensively in France, U.K., and Japan almost at the sametime. The result has been that today in Japan, as may be seen in Fig. 2, most of our LD converters have been remodeled into the top and bottom blowing version.

Incidentally, this bottom blowing oxygen converter was developed by Maxhütte of Germany, and was named OBM. It was then taken up by U.S. Steel, and they called it Q-BOP. Now, it was about a decade ago that I was asked by a Thyssen engineer if I knew what OBM was an abbreviation of. Well,

Fig. 2. Emergence of the top and bottom blowing converter.

Source: M. Hanmyo: The 100th-101st Nishiyama Memorial Seminar, ISIJ, Tokyo, (1984), 203.

he told me that it stood for Ober Bayerische Musik, and I thought he meant rather sarcastically that the process was popular only in the Southern Germany. But I have heard that Thyssen too had their LD converter converted to the bottom blowing. Then, in 1978 or thereabout, Maxhütte conducted experiments of melting a lot of scrap by providing a top-blowing lance to their OBM, and called it OBM-S, with an S for scrap. People told me then that when

Thyssen remodeled their LD to be bottom blowing, they left the top-blowing lance intact.

Whatever early history was, the top and bottom blowing technology has since evolved into a multitude of practicable methods, one subtly differing from next in the kind of gas to be blown from bottom as summarized in Table 2, or in the form of the tuyere to be used as illustrated in Fig. 3, or if CaO is blown in or not.

Table 2. Characteristics of various combined-blow processes.

Bottom-blow gases		Means of bottom-blowing	Characteristics		Processes
			Strengths	Weaknesses	
Inert gas (Ar, N ₂)		Porous bricks or permeable bricks	<ul style="list-style-type: none"> Low capital investment Easy dehydrogenization Interruption of bottom-blowing allowed 	<ul style="list-style-type: none"> Cost for Ar gas N₂ pick-up by steel* 	LBE
		Pipes	<ul style="list-style-type: none"> Low capital investment Easy dehydrogenization 	<ul style="list-style-type: none"> Cost for Ar gas N₂ pick-up by steel 	LD-KG LD-AB LD-OTB
Air (Air+N ₂)		Double-tube tuyere (CO ₂ -cooling)	<ul style="list-style-type: none"> Low capital investment Little H₂-pick-up of steel Low gas cost 	<ul style="list-style-type: none"> N₂ pick-up by steel 	BAP
CO ₂ gases (CO ₂ +O ₂)		Double-tube tuyere (CO ₂ -cooling)	<ul style="list-style-type: none"> Recycling of converter gas Easy dehydrogenization 	<ul style="list-style-type: none"> Endothermic reaction of CO₂+C=2CO Cost for CO₂ gas 	STB
O ₂ (O ₂ +C _m H _n)	No CaO powder	Double-tube tuyere (Hydrocarbon-cooling)	<ul style="list-style-type: none"> Exothermic reaction of O₂+2C=CO Bath stirring by CO bubbles 	<ul style="list-style-type: none"> H₂ pick-up by steel High capital investment Cost for coolant gas 	LD-HC LD-OB LD-OTB HK-CB
	With CaO powder	Double-tube tuyere (Hydrocarbon-cooling)	<ul style="list-style-type: none"> Same as above In-blowing of active CaO 	<ul style="list-style-type: none"> H₂ pick-up by steel Cost for coolant gas Cost for making CaO powder High investment cost 	KMS K-BOP

* Can be held to minimum by a special technique.

Fig. 3. Bottom-blow nozzle.

Source: M. Hanmyo: The 100th-101st Nishiyama Memorial Seminar, ISIJ, Tokyo, (1984), 204.

From the quantitative studies of the stirring force of bottom-blown gases into the steel bath, we have learnt that the stirring action is different with the kind of gas used because of the reaction between blown-in gas and steel bath. For example, when O_2 or CO_2 is bottom-blown, a strong stirring force is developed while the carbon is still high enough, but the stirring action rapidly diminishes in the low carbon range of, say, $C < 0.10\%$. Here, strong stirring means a preferential oxidation of C, or fast decarburization, and weak stirring implies a delay in C supply to the reaction sites, meaning the oxidation of Fe is apt to occur. Based on these notions, parameters that determine proper oxygen feeding rates and bottom-blown gas flow rates to attain the target (T.Fe) have been proposed.

Intensification of stirring has brought about an expectation of further improvements in the yield of Cr or Mn, or even positive reduction of their ores. Indeed, they may be said to be adding new functions to the converter. When applications to such new technical field such as gasification of coal or smelting reduction of ores are considered, however, I must say that there is much to be done in the quest for optimum stirring conditions and in establishing on optimum nozzle design. I would, therefore, hope for further development in those fields.

IV. Hot Metal Pretreatment

Today, there is another prominent trend in steel-making besides the top and bottom blow. It is partitioning refining, namely, a combination of hot metal pretreatment—decarburization in the converter—ladle refining.

As the LD converter process became the mainstream of steelmaking, purification of converter steels became the subject of study. Whereupon, desulfurization of hot metal was developed energetically and duly put to practice. Along with it, moreover, vacuum degassing became popular.

In the desulfurization of hot metal, the old method of adding soda ash to utilize the dynamic motion of hot metal for stirring became not good enough because of low temperature and other reasons, and various new methods of stirring were devised and tried in various new desulfurization processes, as may be seen in Fig. 4. In the end, the porous plug method and the injection lance method, in which powerful stirring is achieved by the gas blown in through the porous plugs provided at the ladle bottom of the former, or by the carrier gas on which the desulfurizer agent is blown into the metal through a lance in the latter, have survived aided by improvements achieved in the refractories.

There have been many exotic inventions. One such idea that I still remember was what an European gentleman tried to sell me some twenty years ago. He called it the "Resonator", and according to this man, if we are to line a ladle in an elliptical cylinder and rotate it, the hot metal bath within should start resonating at a certain rotation speed to generate waves. Then by tilting the ladle, we should have

stirring in the up and down directions as well. Well, I never have heard his invention materialized.

As the partitioning refining spread, and as the tapping temperature became higher for the conveniences of continuous casting, instances of performing dephosphorization with the hot metal pretreatment increased. To do this, however, two steps, first oxidizing P then forming slag for it, are necessary. This means either O_2 itself or an oxidizer as well as dephosphorizer have to be supplied efficiently, for which stirring will become the critical factor.

Furthermore, the trend is to perform desiliconization outside the furnace. Generally, this is done at the tapping runner by either projecting or spraying the oxidizer, such as a mill scale, on to the hot metal stream. But it is known that desiliconization takes place only at cascading parts, where the hot metal and desiliconizer are mixed well, and that the slag-metal reaction in the static bath hardly progresses.

You would agree that stirring is the most important single factor also for pretreatment.

V. Ladle Refining

As purification of converter steel progressed, vacuum degassing became widely spread. Here, methods of analysis of molten steel flow that were developed for the LD converter, were applied to the DH and RH to quantify the metallurgical effects and raise process efficiency.

In the DH, for example, the traditional designing for a large bath surface area in emphasis of availability of reaction interface has been changed to designing for larger stirring force by allowing greater vertical motion. In the RH, as intensification of recirculation of molten steel has become known to increase treatment effects, steels of lower carbon, though better homogenized, have become produced in the same treating time by enlarging the immersion tube inner diameter or by increasing the Ar flow rate. A consequence is that today both DH and RH have been recognized as indispensable in making special steels with a converter.

As the refractories were improved, furthermore, the stirring technologies that were developed for hot metal desulfurization became applicable to ladle refining. The result has been the development of various processes as shown in Fig. 5, owing to which making of special steels with a converter has become so much easier. Nowadays, the gas bubbling method and the electromagnetic stirring method are available besides the vacuum treatment method, so that, when a single method is deemed insufficient, any of these may be used complementarily. Not only that, various measures are being taken, such as performing a part of the decarburization by blowing O_2 or compensating for the temperature drop during treatment by equipping the ladle with a heating apparatus.

As for the Ar bubbling with regard to homogenizing the steel composition and to accelerating separation and ascension of nonmetallic inclusions, its effectiveness has been demonstrated indubitably by presenting a decrease of nonmetallic inclusions in terms of the

Fig. 4. Various hot metal desulfurization processes.

Source: Genzai no Kinzokugaku, Seiren-Hen I (The Modern Metallurgy, Refining Processes I), ed. by The Japan Inst. Metals, Maruzen, Tokyo, (1979), 222.

decrease in the total oxygen in steel. Indeed, to make clean steel, it used to be in the olden times “keep the steel still”, but nowadays it is “stir it up”. This has revolutionalized the technological notion of deoxidation also.

To meet the demand for continuous casting, on the other hand, the composition and temperature of the molten steel had to be controlled in a narrow area. This has increased the importance of ladle refining, which in turn is being refined mostly by means of improving gas stirring. Speaking of gas stirring, even with the ASEA-SKF process, which utilizes electromagnetic stirring, concurrent application of Ar bubbling is known to raise the refining

ability and to lower H_2 in steel.

So, you will agree that stirring is a basic element in ladle refining, too.

VI. Concluding Remarks

I have briefly described the evolution of steelmaking processes and the changes of the stirring technology that were made in it. I have also described how the progress of stirring was important in establishing the mass production processes of steel and the processes of making high grade steels, so important in fact that features of those steelmaking processes that have been industrialized today can hardly be clearly defined without referring to stirring.

Fig. 5. Various ladle refining processes.
Source: B. Eto: The 27th-28th Nishiyama Memorial Seminar, ISIJ, Tokyo, (1974), 5.
T. Ito: The 72nd-73rd Nishiyama Memorial Seminar, ISIJ, Tokyo, (1981), 162.

Though I did not go into any detail, no big words are needed to see that the simulation experiments with water models centering on dimensional analysis and the computer numerical analysis have contributed greatly to the implementation of all those stirring methods, thus accelerating the industrialization of hot metal pre-treatment and ladle refining.

Since steelmaking processes are essentially the batch refining process, and since the temperatures and specific gravities concerned are both especially high, however, no ideal stirring method can be found. Also, the states of the steel bath motion can be grasped

only indirectly. Therefore, in the matters of predicting reaction or designing an apparatus, much still remains dependent on experiences.

Now we are in a position where we may expect successful development of new steelmaking processes, including smelting reduction. And this is why I call for a renewed endeavor to advance the quantification of the flow in steelmaking processes and to develop, by the force of industry and academy combined, new processes that will allow us to lead the world by making an effective use of stirring.

I thank you for your attention.