Refining Practice and Application of the Ladle Furnace (LF) Process in Japan*

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Synopsis
Since 1971, Daido Steel Co., Ltd. has developed the LF process, a ladle refining process which depends primarily on slag refining, aiming an ideal performance of reduction refining instead of electric arc furnace. The main feature of this ladle technology exists in refining under non-oxidizing atmosphere and acceleration of slag-metal reaction through stirring by Ar gas injection, for a desired long time due to the temperature compensation by arc heating. It is possible to obtain clean materials having low oxygen and sulfur levels around 10 ppm, or inclusion rating of approximately 1.0 to 0 for every type specified by ASTM-A.

At the early stage of development, several LF units were applied only for the production of high grade steels. In recent years, the application has extended to whole steel industry not only for the quality improvement, but for cost reduction, production increase and especially ladle-CC matching in sequence casting. In 1983, there are 24 LF installations in domestic steel works including 3 integrated steelmakers and the total LF steel will exceed 7 million t.

Many steelplants in Japan are now equipped with FAF(BOF)-LF-RH-CC combined line for high quality steels, in which reduction refining is exclusively entrusted to LF. The portion of special steels produced by this steelmaking process is expected to increase still further.

I. Introduction
Among the diverse secondary steelmaking process existing today, ladle furnaces with electrode heating system have occupied an important position in steel-making owing to the flexible and versatile applicability. The LF process, developed by Daido Steel Co., Ltd. in 1971, is a unique ladle furnace technology which adopts slag refining for the principal refining method instead of vacuum treatment in other ladle furnace processes. The LF technology has been successively introduced in many domestic steelplants and is now approved by whole steel industry to be convenient and widely available in steelmaking, irrespective of the grade of the products. The process has been also licensed to several foreign firms.

In this paper, the Daido ladle furnace process is briefly explained as to process functions and refining effects as well as the practical application in all LF operating steelplants in Japan.

II. Features of LF Process for Steel Refining
The characteristic of LF refining can be expressed in a short wording, to be a secondary steelmaking process which promotes all of reduction refining stages under ideal conditions. Reduction refining has been a special metallurgical field belonging only to EAF.

The initial purpose of LF development was in transferring reduction refining from EAF to the ladle.

Accordingly, LF comes to employ basic white slag as a means of refining, not depending on vacuum degassing like other secondary steelmaking processes. This process covers all functions in reduction period in EAF, namely deoxidation, desulfurization, inclusion removal, adjustment of temperature and chemistry of molten steel, reduction of metal oxide in the slag, alloy addition of a large quantity and slag off; all of these operations can be achieved with easier handling, higher quality and better reproducibility than in usual EAF melting. If it is necessary, vacuum degassing can be incorporated before or after the proper refining of LF. Practically, several types of combination are used in the LF-V operation.

Figure 1 shows the principle of LF refining. The furnace consists of a ladle with a porous brick at the bottom for Ar injection to induce molten steel stirring and accelerate slag–metal reaction, a lid for sealing the vessel chamber to keep the non-oxidizing atmosphere, and an electrode heating system in the upper part. For teeming, a slide gate is employed in order to withstand a long period of holding.

The arc heating is usually applied in the form of slag submerged arc. It provides a better heating efficiency and a favorable protection of lining refractory, due to the absence of arc radiation. Furthermore, the immersed graphite electrodes react with slag oxide to accelerate the rate of slag reduction.

Fig. 1. Principle of LF refining.
The strongly reducing white slag can enhance refining capacity of the process.

There are four refining functions which are unique to the LF process as described below.
1) Non-oxidizing atmosphere
2) Ar gas stirring
3) Submerged arc heating
4) Existence of basic white slag

They are, as the slag deoxidation by electrodes, highly interdependent. The interaction of these functions forms a desirable circumstance for refining and results in a big difference in material quality or reproducibility from ordinary EAF steels.

Thus, at the beginning of the development, LF was applied only for high grade steels in expectation of improved quality, decrease of rejects and lowering cost of raw materials. Especially it exhibited an obvious advantage for high alloy steels which requires exact adjustment of complex composition, good yield of valuable alloys and a large amount of alloy addition.

Through the operation for these special steels, some unique refining techniques have been established. Reduction of metal oxides in slag in a LF vessel can be taken as an example. Owing to the favorable atmosphere and stirring effect, a high efficiency is assured in acceleration of reduction.

Diffusion deoxidation is another example which uses no deoxidizers for oxygen refining but relies only on oxide absorption by the white slag. The atmosphere and stirring movement in LF also produce a decisive effect on this deoxidation method.

As to the vacuum degassing process to be combined with LF, RH is most used in present steelmaking. Since the presence of slag bulk in a LF vessel does not hinder RH operation, these two processes are very suitable for combining together in same steelmaking line.

The typical forms of the combination are shown in Fig. 2, Type I indicates single LF refining without vacuum degassing. In producing big forging ingots, however, LF steel is often poured into a vacuum casting unit. Type II is a combined process of LF and RH. Heating and degassing are separated in this operation. In type III the LF vessel serves as a vacuum ladle. In contrast to RH degassing, a large quantity of slag is not desirable for degassing efficiency of this type.

The appearance of a large LF facility is shown in Photo. 1.

III. Refining Modes and Performances

At present, the LF process is utilized for many different applications having various refining modes. Figure 3 illustrates these modes by a 30 t LF unit at Shikukawa Plant, Daido Steel Co., Ltd., as a typical example. This steelmaking shop produces rather big forging ingots weighing 4 to 30 t which are usually degassed by a vacuum ladle degassing method. Shikukawa Plant is suitable as a model case of multi-form LF processing, since it handles many high quality grades of steels for various uses, from low alloy construction steels to superalloys. For degassing of LF steel, the LF–Vacuum combination of type III in Fig. 2 is employed.

Processing mode I shown in the upper line in Fig. 3 gives a basic operation for the products in ordinary qualities. Molten steel after oxidation refining is tapped from EAF into the LF vessel. The slag is removed by 50 to 90% and then deoxidizers
and some quantity of slag formers are added to promote reduction refining in parallel with the vacuum degassing. An especially high removal of sulfur or non metallic inclusions is not intended in this processing. The degassing applied here should, however, be effective enough to prevent hydrogen induced flakes. The steel chemistry and temperature are also strictly regulated. The refining time of about 40 min is nearly equal to the full reduction period in EAF.

Mode II in the second rank is a typical and widely used processing for high grade steels in which a high cleanliness is required. Preceding to the refining, EAF slag in LF vessel is completely removed and a sufficient volume of slag formers and deoxidizers are added. Then vacuum degassing and the slag-metal stirring under heating arcs refine the molten steel to attain the aimed levels of gas contents, impurities and inclusions.

When VAR electrodes of high alloy steels or super-alloys are refined, vacuum treatment is usually omitted as seen in mode III.

For extra low sulfur steel, a double slag method is applied like mode IV, spending twice as much time as the basic pattern.

Mode V gives the operation for vacuum carbon deoxidation. This deoxidation method is sometimes specified to some rotor forging materials and does not allow to add any metallic deoxidizers. Besides the specified vacuum deoxidation, an application of white slag for oxygen absorption is a useful means to attain a good cleanliness. For effective diffusion deoxidation, controlled atmosphere and slag-metal mixing are needed and they are well satisfied in the LF vessel.

Mode VI provides a thorough degassing by which even VIF melting can be substituted. Due to the application of a double vacuum treatment, the refining spends a long operation time of about 2 hr. Typical products for this processing are Ni base electronic materials for the intensified removal of gaseous elements.

Mode VII in the lowest line shows a special use for metal oxide reduction. In the AOD process, metallic chromium is recovered out of oxide slag by using silicon as the reductant. The high recovery in AOD owes to the Ar gas stirring and the non-oxidizing atmosphere. The condition is more favorable in LF vessel and a long duration for good reduction is applicable because of the temperature compensation system.

Being different from AOD, the oxide reduction in LF is available to all kinds of steels. The application of this processing to high alloy tool steels or high speed steels has proved big cost savings by the complete recovery of alloying elements, i.e. W, V, Cr and Mo.

As to the treated quantity, mode I is the first and occupies the major part. For productivity increase, there is not so much effect in LF operation unless a big tonnage is transferred from EAF to LF for the reduction refining. Mode II takes the second position because this is a general processing for clean steel and there are many products for this pattern. The ratio of other modes may amount to 10 % in total.

Two refining charts taken from the operation of the 30 t LF in Shibukawa Plant are indicated in Figs. 4 and 5.
exhaustive desulfurization, then Ca metal is fed into the steel in a form of cored wire to stabilize the remainder of sulfur. The refining slag is formed by adding CaO and CaF₂ to have an unordinary high basicity of CaO/SiO₂=8. Sulfur is thus reduced from the initial level of 96 ppm to the final 4.4 ppm as an average value of seven heats. The distribution ratio (S)₀/₄ also attains an outstanding value of 470.

The non metallic inclusions are completely modified in their shapes as indicated in the next figure.

Figure 6 illustrates the effect of LF refining on steel cleanliness. Four refining methods are compared in the diagram. Methods I and II represent ordinary EAF refinings without and with RH degassing, and method III or IV is the combined process of EAF–LF–Vacuum Degassing. All the materials compared are low alloy construction steels. A table of impurity levels is given in the upper part of Fig. 6.

Method III belongs to the usual LF refining for elaborate clean steel, however, in method IV, calcium is added to the finished steel in LF for shape control of inclusions.

A remarkable difference in type A is observed between the rating of non-LF and LF treated steel due to the decisive difference of sulfur contents. For evaluation of oxides, the higher oxygen level of method I causes a protrusion in the rating of type B, but RH refined steel (II) and LF–RH steel (III) are almost on the same level in regard to types B and D.

In method IV, inclusion of type A is not determined at all and there is little indication of type B, which suggests inclusions in this steel are completely transformed into type D by the calcium shape control.

Another result on cleanliness is recorded in Fig. 7. It provides an influence of LF refining on the materials for consumable electrode remelting processes. Inclusion ratings of ESR or VAR steels with and without previous LF refining are compared in the two diagrams, in which an obvious improvement can be seen in all inclusion ratings of LF steel. ESR and VAR processes are essentially effective means for inclusion separation. Still the previous LF refining makes the remelted materials so clean that the figure shows a remarkable decrease of A type in VAR, and of oxide inclusions (B, D) in ESR.

IV. Various Usages of the LF Process

The current usages of the LF process are shown in Fig. 8. The process functions are placed at the center while the actual utilisations are shown on the periphery. The encircled numbers beside the arrow heads denote the process functions contributing to the pointed application.

For several years after the development, application of LF has been limited to refining of high grade steels. Later on, the rationalization of melting and casting processes began to be attempted and the field of utilization has widely extended.

Since LF refining reduced the refining burden of EAF, productivity of EAF ought to increase remark-
ably. The combination of BOF and LF enables reduction refining to be applied to BOF steel. It promotes production of high quality steels or newly developed products in the BOF plant. Furthermore, the function of strict regulation of steel chemistry and temperature can be used for a narrow range assurance of steel hardenability or solution of CC problems in special steels having difficult casting conditions.

A noteworthy application which has increasingly become popular in these three years is the long time holding of molten steel for smooth sequence casting in CC operation. The combined steelmaking of LF–CC fulfills three expectations, namely, an increase of EAF melting cycle, improvement of steel qualities and matching of pouring with CC to realize a long sequence casting. Because of these possibilities, LF unit now comes to be indispensable to CC shop.

The main four internal special steel makers in Japan which have successively introduced CC equipment, have also installed LF unit in the same manner, because of the strict quality required in continuously cast special steels.

V. Actual Utilization of Daido Ladle Furnace in Japan

At present, the LF process is widely appreciated by the steel industry. The number of installation is expected to still increase for coming several years. The reason may exist in the high refining effect, versatile application, simple furnace structure and the high economical gains compared with the amount of investment. At the beginning of 1983, Daido ladle furnaces which have been installed in steelplant in Japan have attained 24 units. They are distributed to 6 integrated, 6 ordinary EAF steel and 9 special steel plants. There are also 2 LF plants in foreign countries.

The location of these domestic steelplants is illustrated on the map of Japan in Fig. 9 together with the capacities of the refining ladles. Figure 10 shows the yearly growth of LF installation. The names of LF plants are entered in the small frames at the lower space. As described before, from the first installation in 1971 to 1977, the purpose of LF refining was restricted to special steels and the total refined tonnage remained at a rather low level of 0.2~0.3 million t/year. In the year 1977, an ordinary steelplant adopted a complete combined operation of whole EAF heats with the LF refining, with intention of
improving the process flow and accordingly, to increase the production. Along with an increased number of EAF plant attempting the same operation, tonnage of LF steel began to rise steeply. Further, five major integrated steelplants successively introduced big LF units in their BOF-CC lines. Thus, cumulative LF capacity in Japan attains to 2 075 t and the annual tonnage of LF steel is estimated to be more than 7 million t in 1983.

Figures 11 to 13 denote the way of use in various LF steelplants, in brief circle diagrams. Essentially LF refining does not depend on any vacuum treatment, however, the operation is often combined with another degassing process, aiming at an intensified hydrogen removal. Many steelplants have been equipped with some kind of vacuum degassing before LF installation, and the degassing operation itself becomes easier owing to the temperature compensation.

In this connection the double processing by LF-RH is now taking the leading place for refining high grade steels.

As to the tonnage proportion in each type of steelplants the total LF steel is roughly divided into three equal parts. At present, the integrated steel industry occupies the first one third, EAF ordinary steel has the second, and EAF special steel takes the rest, as seen in Fig. 12.

The casting method of LF treated steel is overwhelmingly depending on CC and the tendency has been particularly accelerated in these three years. The dominance of CC is evident in Fig. 13. With regard to continuous casting of high grade steels, there are many subjects to be solved by utilizing LF functions, for example, improvement of steel cleanliness, proper use of deoxidizers, strict control of steel temperature and feeding the ladle steel exactly on time, etc.

Figure 14 is a frequency diagram classified by the purpose of LF processing in all internal LF steelplants. There are various applications according to requirements of individual steelplant, however, the figure shows that the most common purpose for all plants is found highest in refining high grade steels of good cleanliness. Yet, as it is difficult to estimate economical effect of the quality improvement, most plants have other operation purposes which provide distinct profits to be worthy of seeking after. These items are, productivity increase, process rationalization of high grade steels and stable operation of sequence casting in CC etc., which are also seen in Fig. 14.

VI. Coming Combined Process for Mass Production of High Quality Steels

The emergence of various secondary steelmaking
The tendency is now so accelerated by the advanced introduction of LF that the role of EAF seems to be more and more restricted to the range of melting and oxidation refining. The combination of BOF and LF also comes to display the excellent quality levels, and the extinction of long years' superiority of EAF steelmaking is now undeniable from the aspect of refining.

A summary of recent progress in domestic steelmaking system for high quality materials is shown in Fig. 15. The arrangement of the new steelmaking line, i.e., primary melting–LF–RH–CC, is now completed or underway by many steelplants. As seen in the figure, the primary furnace takes only oxidation refining, and the needed reduction refining is completely transferred to LF. The characteristc of the new line exists in multiple processing by combining several specialized unit refining methods. The combined line may be evaluated to have the advantage of high efficiency and economic advantage compared with the conventional steelmaking. In a few years, the new combined process will take the greater part of special steel production in Japan.