# Development to Minimize Iron Loss at Oita Works

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### Abstract

At Oita Works, use of a Multi-Refining Converter method (MURC) that performs de-Si/ de-P blowing and de-C blowing in one vessel with intermediate slag exclusion has been expanding. As a result, an annual capacity of 10 million tons of one steelmaking plant was achieved with the entire amount of the hot metal pre-treatment process to produce general grade and high-grade steel production. The main feature of this MURC process is that heat loss is minimized by performing hot metal pretreatment without transferring hot metal to a container and also by reusing BOF slag in hot conditions. This creates a thermal margin and enables the use of a large amount of scrap when increasing production. On the other hand, high-molten iron blending operations require the input of a large amount of iron oxide as a coolant, resulting in a poor iron yield becoming apparent. In addition, slag and dust recycling has been expanded to cope with the rise in impurity concentration ([Si], [P], [S]) in hot metal accompanying the deterioration of raw material quality such as iron ore and coke and further reduce by-products. This report describes the efforts to reduce slag emissions in the refining process and iron loss reduction by improving the utilization method of iron oxide.

#### 1. Introduction

The steelmaking plant of the Oita Works (hereinafter referred to as the Oita steelmaking plant) expanded the application of the multirefining converter (MURC) process that desiliconizes and dephosphorizes the hot metal (blow 1) in a basic oxygen furnace (BOF) and then decarburizes the hot metal through intermediate deslagging (blow 2) as shown in **Fig. 1**. Specifically, the entirety of the MURC process was enhanced to adapt to the manufacture of carbon steels and high-grade steels by refining the hot recycling technology and developing the high-speed blowing technology.<sup>1,2)</sup> As a result, the Oita steelmaking plant improved the hot metal pretreatment ratio as shown in **Fig. 2** and established a 10 million ton annual production system as a single steelmaking plant.<sup>3)</sup>

The most noteworthy feature of the MURC process is that it decarburizes the hot metal in the same BOF through intermediate deslagging and without transferring the hot metal after desiliconization and dephosphorization from one ladle to another and hot recycles the blow 2 slag to minimize the heat loss.<sup>4,5)</sup> A sufficient thermal margin was thus generated to allow the use of a large amount of scrap during increased production. When the hot metal blend ratio is set high to minimize the use of purchased scrap, it is necessary to charge a large amount of solid iron oxide (hereinafter referred to as the iron oxide). The problem of declining iron oxide yield is emerging. Furthermore, the hot metal pretreatment process must be especially improved to cope with the increase in the concentrations of impurities ([Si], [P], [S]) in the hot metal with quality deterioration of iron ore, coke, and other raw materials. It is also necessary to reduce the amounts of by-products generated.<sup>6</sup>)

Against the above background, we have worked to reduce the amount of slag generated in the refining process from the main viewpoint of recycling the slag and dust and to reduce the iron loss by improving the use of the iron oxide. The results we achieved are reported here.

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Fig. 1 Schematic diagram of the procedure of MURC operation



### Outline of Slag and Dust Flow at Oita Steelmaking Plant and Viewpoint of Iron Loss Reduction Layout of Oita steelmaking plant

The layout of the Oita steelmaking plant is shown in **Fig. 3**. As hot metal pretreatment facilities, there are two torpedo car (TPC) stations, one optimized refining process modified (ORP-M) station, three BOFs (two BOFs in operation and the other BOF on standby), two RH vacuum degassing units, and three continuous casters.

The hot metal pretreatment process adopted in 1986 was the ORP-M process consisting of TPC desiliconization and hot metal ladle dephosphorization and desulfurization. We carried out cost reductions in this way. With the drop in the thermal margin in divided refining and the regulation of the use of fluorspar by the revision of the Soil Environment Standards of the Ministry of the Environment of Japan, we introduced the MURC process, a BOF hot metal pre-

treatment process, in 1998 and have expanded its application since then. We started the hot recycling of slag in the MURC process in 2002. For general steels, hot metal ladle treatment equipment was used as high-speed desulfurization equipment utilizing its immersion freeboard (**Fig. 4**). These efforts greatly improved the MURC process as an environmentally friendly process centered on reducing the amount of slag discharged outside.

#### 2.2 Initiatives to expand slag recycling

**Figure 5** shows the occurrence of slag at the Oita steelmaking plant. Part of the desulfurization slag is directly recycled for sintering. The other slag produced is sent through a slag treatment station to the crushing and screening process for metal recovery. The slag left after the metal recovery is aged to reduce its thermal expansion and is shipped outside the works or recycled and reused at the works. Of 89 kg/t of the slag discharged outside in fiscal 2010, 47



Fig. 3 Layout of refining process in steelmaking plant at Oita Works



Fig. 4 Process flow diagram of refining process in steelmaking plant at Oita Works



Fig. 5 Origin of various slag in steelmaking plant at Oita Works



Fig. 6 Schematic diagram of recycle procedure of BOF slag



kg/t remained within the works. As a result of increased recycling since then, such as use of slag as subbase material and recycling of slag within the works, mainly in the ironmaking and steelmaking processes, no slag remained within the works and slag production balanced slag recycling in fiscal 2014. Especially, the amount of steelmaking slag recycled increased from 3 kg/t in fiscal 2010 to 12 kg/t in fiscal 2014. The initiatives we took in this regard are described later. In addition, 12 kg/t of slag is recycled for sintering within the works and 79 kg/t of slag discharged outside is all reused mainly as subbase material and ground improvement material.

The recycling of the slag at the Oita steelmaking plant is shown in **Fig. 6**. In the MURC process, the blow 2 slag with high basicity was hot recycled to the blow 1 with low basicity to sharply reduce the consumption of quicklime. The separation of high-basicity slag was strengthened to reduce the use of quicklime further as described below.

(1) Recycling of blow 2 slag to TPC desiliconization and BOF

The blow 1 slag and the blow 2 slag were initially recovered together. They were later received with separate slag pans and the blow 2 slag with high basicity alone was recovered for recycling. To use the blow 2 slag for TPC desiliconization, routes for receiving and transporting the blow 2 slag were installed and modified in the crushing process at the submaterial plant and the blow 2 slag was



used for powder production as described later.<sup>6)</sup> When the high Si content of the tapped hot metal raised the Si content of the hot metal charged into the BOF, excess blow 2 slag was recycled to achieve the desired slag basicity.

(2) Recycling of ladle slag

The ladle slag is high in both basicity and  $Al_2O_3$  concentration. The melting point of the slag is decreased by the increase in the  $Al_2O_3$  concentration in addition to the substitution of the CaO source. Since the ladle slag is effective in improving slaggability, it was used in a short-time blow or the blow 1.

The slag recycling situations are shown in **Fig. 7**. As compared with fiscal 2010, the specific amount of slag recycled cold sharply increased in fiscal 2014. As a result, the specific consumption of fresh CaO charged into the blow 1 was substantially reduced as shown in **Fig. 8**.

#### 2.3 Initiatives to expand dust recycling

Main sources of dust in the Oita steelmaking process are ORP-M ladle desulfurization dust and BOF dust. These dusts are recycled to hot metal pretreatment and the BOFs. Part of the BOF dust is transported as raw material for reduced iron to the Hirohata Works. The hot metal pretreatment process at the Oita Works is equipped with dust treatment equipment designed for dust recycling, such as



Fig. 9 Amount of slag discharging outside the recycle system (2010Fy)



Fig. 10 Relation between input iron oxide and T.Fe content in Blow 1 slag

roller mills and dryers, and can produce powdered dust with a moisture content of less than 1% and a particle size of less than 150  $\mu$ m.<sup>7)</sup> The dust drying equipment capacity was increased to increase the production of the dust for supply to TPC desiliconization and to the BOFs. The recycling of the dust in the desiliconization process was promoted to use the dust in place of all the iron oxide required for TPC desiliconization. Equipment to knead, form, and dry the BOF dust is used to recycle the dust in the MURC process. The promotion of dust recycling to the BOFs by the effective use of the agglomeration equipment is described later.

The above initiatives increased the dust recycling to the BOFs and TPC desiliconization from 4.6 kg/t in fiscal 2010 to 8.1 kg/t in fiscal 2014.

#### 2.4 Problem of iron loss in Oita refining process

Main iron losses in the refining process may be broken down into dust, metallic iron in slag, and iron oxide in slag. Flow balance is being attained concerning the amount of slag discharged. If slag recycling is not achieved, difficult-to-recover iron oxide in the slag amounts to an iron loss. It is essential to reduce the amount of valuable iron in the slag to be discharged outside. **Figure 9** shows the amount of steelmaking slag discharged outside and the amount of iron loss at the Oita Works in fiscal 2010. We have endeavored to recycle more of the blow 2 slag and the hot metal slag and to reduce the iron loss. The iron in the blow 1 slag is discharged outside unless it can be recovered by magnetic separation.

Figure 10 shows the relationship between the amount of iron



Fig. 11 Relation between basicity and T.Fe content in Blow 1 slag

ore charged in the blow 1 and the total iron (T.Fe) content of the turndown slag. As the amount of the iron ore charged in the blow 1 increases, the T.Fe content of the turndown slag in the blow 1 increases. As a result of the operation of interrupting blowing at the occurrence of foaming for intermediate deslagging, the blowing time in the blow 1 was about 3 min and was too short for the reduction of iron ore to metallic iron. When the BOF is operated with a high hot metal ratio (HMR), charging a large amount of iron ore to cool the hot metal causes the problem of high T.Fe content.

#### 2.5 Considerations about reduction of iron loss

**Figure 11** shows the results of the test in which the T. Fe content after TPC desiliconization by powder injection is compared with the T. Fe content of the slag after the MURC blow 1 (without use of iron ore). As the basicity (CaO/SiO<sub>2</sub> or C/S) increases, the T. Fe content decreases. At any basicity, the T. Fe content can be greatly reduced by utilizing TPC desiliconization. The iron oxide concentration decreases with increasing basicity, presumably because the increase in the activity of FeO in the slag accelerates the reduction of iron oxide.<sup>8</sup>

Based on the above discussion, the considerations about the reduction of iron loss are shown in **Fig. 12**. To minimize the iron loss in desiliconization and dephosphorization (MURC blow 1), we tried to reduce the slag volume and the iron loss from the unreduced iron ore. Specifically, we increased the recycling of slag by separation and recovery of high-basicity slag as described in 2.2, intensified the desulfurization by TPC powder injection, and utilized iron ore with a low oxidation degree (such as dust).

#### 3. Initiatives to Reduce Iron Loss by TPC Desiliconization

3.1 Measures for expanding application of TPC desiliconization

The process from the TPC treatment plant to BOF charging is illustrated in **Fig. 13**. At the TPC treatment plant, gas and powder are injected through the inner and outer tubes, respectively, of a doubletube lance to perform various treatments. The powder reagents are drawn in the specified blend ratio from the receiver tanks into the lift tank and are pressure fed to the blow tank. The desulfurizer was crushed and supplied at the submaterial plant within the works.

After the TPC treatment, the BF slag and the desiliconization slag formed by desiliconization are discharged together with the hot metal from the TPC into the hot metal ladle. Before desulfurization at the hot metal pretreatment plant, the hot metal ladle is tilted and deslagged with a dragger into the slag pan. The desiliconization slag in the slag pan is transported to the hot metal slag pretreatment plant





Fig. 14 Measures of TPC De-Si without fresh CaO

and cooled.

To recycle the blow 2 slag as a CaO source for TPC desulfurization, a new crushing line was installed at the BOF slag treatment plant to separate and recover the blow 2 slag and to inject the blow 2 slag into the TPC. New equipment was installed to treat the increasing amount of desiliconization slag from the TPC desiliconization. These measures are summarized in **Fig. 14**.

3.1.1 Measures for manufacturing TPC desiliconizer

The TPC desiliconizer is crushed with a roller mill at the submaterial plant. **Figure 15** shows installed and modified equipment on the blow 2 slag powder manufacturing line. The line originally produced quicklime powder for injection into the TPC and hot metal ladle. Given the excess capacity, the blow 2 slag material receiving and transporting routes were installed or modified and used for blow 2 slag powder manufacture. The blow 2 slag contains moisture so that when pulverized and used in that condition, it may aggregate and cause clogging during injection. The hot air from a hot stove



Fig. 15 Manufacturing line of powder material from blow 2 slag

was fed into the roller mill to dry the blow 2 slag.

The desiliconization dust was dried, crushed, and supplied as desiliconizer. The dryer capacity was not large enough for dust manufacture. As shown in **Fig. 16**, therefore, a new dryer was installed to increase the dust manufacturing capacity. This made it

possible to secure a desiliconization dust manufacturing capacity of  $3\,000$  t/month.

3.1.2 Measures for improving desiliconization slag treatment capacity

The desiliconization slag generated in a larger amount by the expansion of the desiliconization capacity is a slag with low basicity and high fluidity. Since desiliconization is performed from a highsilicon region, graphite precipitated from the hot metal remains in a large amount in the desiliconization slag. It is thus necessary to improve the slag treatment capacity after taking the measures for cooling the fluid slag with high efficiency and for preventing graphite dust from scattering.

When the desiliconization slag is water spray cooled from the top of the slag pan, it is solidified on the surface due to its high fluidity making it difficult for the water to penetrate into the slag bath. The desiliconization slag thus takes about 24 h to cool. The hot turnover method that can cool the slag in a relatively short time was adopted to increase the treatment efficiency. Figure 17 shows the flow of desiliconization slag treatment by the hot turnover method. The desiliconization slag is turned over hot in a building with dust collection equipment to prevent the graphite dust from scattering. Large lumps are crushed and the slag is primarily cooled by water spraying. The slag is then transported to a secondary cooling station and again spray cooled to improve the efficiency of cooling. The hot turnover method provides a much wider surface area than water spray cooling from the top of the slag pan and can cool the slag in a shorter time. Figure 18 shows the temperature change of the desiliconization slag during cooling by the hot turnover method. This method made it possible to cool the desiliconization slag in a short time to below the 100°C standard established in consideration of the heat load on transport vehicles.

#### 3.2 Evaluation of reduction degree of iron oxide by TPC desiliconization

To evaluate the reduction degree of the iron oxide by TPC desiliconization, we sampled and analyzed the slag after TPC desiliconization, calculated the amount of total iron loss to the desiliconization slag from the analysis values, and determined the reduction degree of the iron oxide (dust and blow2 slag) from the calculated amount of total iron loss. The reduction degree is defined by the following equations. The T.Fe content of unreduced iron oxide in Equations (2) and (4) was calculated from the T.Fe content difference between the TPC desiliconization slag when no iron oxide was charged and the TPC desiliconization slag when iron oxide was charged. The Appendix shows the methods for calculating the amount of TPC desiliconization slag used to calculate the T.Fe content of the TPC desiliconization slag in Equation (4).

• Reduction degree of iron oxide

= T.Fe content of reduced iron oxide/T.Fe content of charged iron oxide (1)

• T.Fe content of reduced iron oxide

= T.Fe content of charged iron oxide – T.Fe content of unreduced iron oxide (2)

- T.Fe content of charged iron oxide
- = Amount of charged dust  $\times$  T.Fe content of dust + Amount of blow 2 slag charged  $\times$  T.Fe content of blow 2 slag (3)
- T.Fe content of unreduced iron oxide
- = T.Fe content of TPC desiliconization slag T.Fe content of TPC desiliconization slag without iron oxide charge (4)

**Figure 19** shows the relationship between the T.Fe content of charged iron oxide and the T.Fe content of TPC desiliconization slag. As the amount of iron oxide charged increases, a slight amount of the T.Fe content of unreduced iron oxide in the desiliconization slag remains. **Figure 20** shows the relationship between the T.Fe content of charged iron oxide and the total iron content of reduced iron oxide. The linearly approximated slope of the plots in Fig. 20 indicates the reduction degree of iron oxide. The reduction degree by TPC desiliconization is very high at 92% and shows that iron can be recovered from iron oxide with high efficiency.

Immersion treatment

**24**h

10 000



Fig. 18 Cooling time of De-Si slag





The T.Fe content of iron oxide (dust and blow2 slag) is mainly reduced by the following desiliconization reaction and recovered as iron.

$$2(\text{FeO}) + \underline{\text{Si}}(\text{mass}\% \text{ in Fe}) = 2\text{Fe}(1) + (\text{SiO}_2)$$
(5)

TPC desiliconization is performed by the powder injection method. Since the desiliconization reaction proceeds while the in-



Fig. 19 Relation between input T.Fe from iron oxide and T.Fe content in De-Si slag



Fig. 20 Relation between input T.Fe from iron oxide and reduced T.Fe from iron



Fig. 21 Reaction mechanism of De-Si by TPC injection method<sup>9)</sup>

jected desiliconizer (gaseous oxygen and iron oxide) floats through the hot metal (transitory reaction) as shown in **Fig. 21**, the desiliconization efficiency is high.<sup>9)</sup> Kaneko and Matsuzaki<sup>10)</sup> indicated that when iron oxide is top charged, the T. Fe content of the top slag increases to retard the reduction of iron oxide. The optimum T. Fe content of slag in the MURC process is considered to be 15 to 20% to carry out the dephosphorization reaction with low basicity and high oxygen potential.<sup>11)</sup> The iron content of iron oxide can be recovered with high efficiency by preferentially recycling the dust and blow 2 slag to TPC desiliconization for the TPC powder injection method with a lower T. Fe content than in the MURC blow 1.

## **3.3** Reduction of iron loss by recycling of blow 2 slag to TPC desiliconization

Powdered quicklime was conventionally used as a CaO source for TPC desiliconization. The blow 2 slag was made recyclable to minimize the amount of desiliconization slag. The manufacture of blow 2 slag powder for TPC powder injection was made possible by the installation and modification of blow 2 slag receiving and transporting routes and by the diversion of the existing hot stove for drying the powder in the roller mill.

**Figure 22** shows the relationship between the specific oxygen supply T.O in consideration of 10% of the effective oxygen content (FeO, Fe<sub>2</sub>O<sub>3</sub>, etc.) of gaseous oxygen, dust, and blow 2 slag and the desiliconization reaction capacity coefficient  $\ln([Si]_{i}/[Si]_{r}$  (where  $[Si]_{i}$  is [Si] before treatment and  $[Si]_{r}$  is [Si] after treatment). The slope of the plots indicates the desiliconization efficiency. The slope of the  $\ln([Si]_{r}/[Si]_{r})$  plots with injection of gaseous oxygen, dust, and blow 2 slag approximately agrees with the slope of the  $\ln([Si]_{i}/[Si]_{r})$  plots with injection of gaseous oxygen, dust, and plots with injection of gaseous oxygen, dust, and the seen that the iron oxide in the blow 2 slag was reduced and that the oxygen content contributed to the desiliconization of the hot metal.

#### 3.4 Effect of TPC desiliconization

As shown in **Fig. 23**, TPC desiliconization of the tapped hot metal from the silicon content of 0.58% provided a desiliconization width of 0.15% and reduced the silicon input to the BOF to 0.43%. Also, the specific consumption of desiliconization dust increased by 7.4 kg/t from 0.3 kg/t in fiscal 2010 to 7.7 kg/t in fiscal 2014. As described above, use of desiliconization dust in TPC powder injection with a high reduction degree of 92% helped to reduce the iron loss and also to reduce the T. Fe content discharged outside by 0.6 kg/t.



Fig. 22 Relation between T.O (gaseous oxygen+Effective oxygen content from dust and Blow 2 slag) and ln([Si],/[Si],<sup>6</sup>)



Fig. 23 Relation between hot metal (HM) [Si] and input [Si] to BOF

## 4. Initiatives to Reduce Iron Loss by Improvement of Reduction Efficiency in BOF

#### 4.1 Considerations about reduction of iron loss in BOF

When the BOF is operated with a high hot metal ratio, the very low heat loss, the largest characteristic of the MURC process, tends to increase the amount of the coolant charged into the BOF. Let us consider iron oxide as coolant. The consumption of iron oxide in TPC desiliconization as described above provides the effect of reducing the iron loss due to a high reduction degree. However, the supply amount of dust as iron oxide is limited and the use of iron oxide in TPC desiliconization is limited from the standpoint of securing the heat required for desulfurization. As a result, a large amount of iron ore is charged into the BOF as iron oxide for cooling.

Let us now turn to the reduction reaction of iron ore. It is reported that the reduction reaction of iron ore by carbon in the hot metal is higher than that achieved by other reduction methods as shown in **Fig. 24**.<sup>12)</sup> The smelting reduction of iron ore in steelmaking has long been studied as a promising direct ironmaking process as compared to the indirect ironmaking process established by the BF steelmaking process.<sup>12, 13)</sup>

The reduction reactions of iron ore proceed in the order of  $Fe_2O_3$ (s) $\rightarrow$ Fe<sub>3</sub>O<sub>4</sub>(s) $\rightarrow$ (FeO) $\rightarrow$ Fe(l). The reduction reactions of molten FeO proceed as shown by the equations below.<sup>12, 14</sup> The reduction reaction rates are presumed to be as calculated by the complex combination of the following equations.14, 15)

- (i)  $(FeO) + \underline{C}(mass\% \text{ in } Fe) = Fe(l) + CO(g)$  (6)
- (ii)  $(FeO) + CO(g) = Fe(1) + CO_2(g)$  (7)
- $CO_2(g) + \underline{C}(mass\% \text{ in Fe}) = 2CO(g)$  (8)
- (iii)  $(FeO) = Fe(l) + \underline{O}(mass\% \text{ in Fe})$  (9) C(mass% in Fe) + O(mass% in Fe) = CO(g) (10)

Iron ore is charged mainly in the MURC blow 1 to lower the hot metal temperature and hence to improve the hot metal dephosphorization efficiency. The treatment time in the blow 1 is short at about 3 min. When a large amount of iron ore is charged, the iron ore cannot be fully reduced. This raises the T. Fe content of the blow 1 slag (Fig. 10). The blow 1 slag is removed by intermediate deslagging before going to the blow 2 for decarburization. If it is not fully reduced, an iron loss results. In the MURC process operating with a high thermal margin and a high hot metal ratio, it is an important issue to increase the reduction efficiency of iron oxide while utilizing smelting reduction with the carbon in the hot metal.

Tsukihashi et al.<sup>14)</sup> reported that prereduction and increase in the reaction interface area are effective for improving the reduction efficiency of iron ore. Also, Fig. 24 shows direct reduction of solid iron oxide and carbon in the hot metal is effective. It is suggested that when iron oxide is added from the top, the particle size and weight of the iron oxide must be large enough for the iron oxide to directly react with the hot metal under the slag. Based on the above results, we studied how to improve the iron oxide reduction efficiency in the BOF.

#### 4.2 Improvement of reduction efficiency by use of BOF dust

**Table 1** shows the chemical composition of iron ore and fine BOF dust. The fine BOF dust originates from finely dispersed dust in a high-temperature environment during BOF blowing. It is not reduced far enough and it contains a large amount of FeO (melting point of 1370°C). It is considered to be advantageous in solubility

Table 1 Chemical composition of iron ore and BOF fine dust

Iron ore (%)	T.Fe	FeO	Fe <sub>2</sub> O <sub>3</sub>	M.Fe
	64	0	91	0
BOF fine dust (%)	T.Fe	FeO	Fe <sub>2</sub> O <sub>3</sub>	M.Fe
	68	47	42	2



Fig. 24 Comparison of reduction speed of iron oxide<sup>12)</sup>

as compared with Fe<sub>2</sub>O<sub>3</sub> (melting point of 1566°C). When the fine BOF dust is agglomerated and top charged, suppression of dust collection loss and direct reduction by contact with the hot metal can be expected. Agglomeration of the fine BOF dust and its reuse in the BOF are considered to be advantageous in solubility and reducibility as compared with the iron ore.

#### 4.2.1 Agglomeration process of fine BOF dust

To reuse the fine BOF dust in the BOF, it is agglomerated with a binder at a dust agglomeration plant (the agglomerated fine BOF dust is hereinafter referred to as dust agglomerate). The manufacturing flow consists of receiving the dust and binder, kneading them while moistening them, extruding them, steam drying the extruded dust agglomerate to a moisture content of less than 1%, and charging it into a ground bunker for BOF submaterials.

4.2.2 Evaluation of reduction degree of iron oxide in BOF

To calculate the reduction degree of iron ore in the BOF, the blow 1 slag was sampled for chemical analysis during intermediate deslagging after iron ore or dust agglomerate was charged during the blow 1. **Figure 25** shows the relationship between the T. Fe content of charged iron oxide and the T. Fe content remaining in the blow 1 slag. When the iron ore is replaced by the dust agglomerate (the dust agglomerate is charged in more than 50 mass% of the charged iron oxide), the T. Fe content remaining in the blow 1 slag is reduced. This means that the reduction degree of the dust agglomerate is higher than that of the iron ore. **Figure 26** shows the reduction degree of iron ore and dust agglomerate. The details of the methods for calculating the iron oxide reduction degree are shown in the Appendix. The linearly approximated slope of the plots indicates the



Fig. 25 Relation between input T.Fe from iron oxide and T.Fe in Blow 1 slag



Fig. 26 Relation between input T.Fe from iron oxide and reduced T.Fe

reduction degree of the iron ore and the dust agglomerate. The calculated reduction degree is 82% for the dust agglomerate and 58% for the iron ore. The reduction degree of the dust agglomerate is shown to be much higher than that of the iron ore.

#### 4.3 Discussion about reduction degree of iron oxide in BOF

The iron ore and the dust agglomerate are top charged into the BOF and are similar to each other in shape and weight. The direct reduction of the solid iron oxide by the carbon in the hot metal is said to progress at high speed. If the reduction of the iron ore and the dust agglomerate proceeds only by this direct reduction, almost no difference is considered to exist in their reduction degree. As shown in Fig. 26, however, some difference occurs in the reduction degree between the iron ore and the dust agglomerate at the end of the blow 1. This is probably governed by one of the following reactions: dissociation reaction of oxygen in the solid iron oxide, dissolution reaction of the solid iron oxide in the slag, and reduction reaction of the molten iron oxide.

The difference in the reduction degree between the dust agglomerate and the iron ore is discussed below.

**Figure 27** shows the relationship between the Fe-O phase diagram and the oxygen partial pressure lines  $p_{02}$ .<sup>16</sup> At the hot metal temperature of 1350°C in the blow 1, the dissociation pressure is 4.3 × 10<sup>-2</sup> atm for oxygen in Fe<sub>2</sub>O<sub>3</sub>, 9.4 × 10<sup>-8</sup> atm for oxygen in Fe<sub>3</sub>O<sub>4</sub>, and 6.6 × 10<sup>-11</sup> atm for oxygen in FeO.

We considered that the oxygen potential in the blow 1 slag where the iron oxide is reduced lies between the C-CO equilibrium and the Fe-Fe<sub>1</sub>O equilibrium and estimated the oxygen potential  $\Delta G^{\circ}$ by using the following equations:

$C(graphite) + \underline{O}(mass\% \text{ in Fe}) = CO(g)$	
$\Delta G^{\circ}(J/mol) = 5150 - 84.39T$	(11)17,18
$1/2\Omega(\alpha) = \Omega(mass\% \text{ in Fe})$	

$1/2O_2(g) \subseteq (1103570 \text{ In FC})$	
$\Delta G^{\circ}(J/mol) = -117110 - 3.39T$	$(12)^{17}$
FeO(1) = tFe(1) + O(mass% in Fe)	

$$O(I) = TFe(I) + O(mass\% \text{ in Fe})$$

$$AG^{\circ}(I/mol) = 117700 - 49.83T$$
(13)<sup>17</sup>

where T is the temperature and t is the stoichiometric coefficient. The activity of C(graphite), the partial pressure of CO, and the activity of Fe<sub>O</sub>(1) are assumed to be 1, 1 atm, and 0.5, respectively.



Fig. 27 Relation between Fe-O phase and oxygen partial pressure<sup>16</sup>



Fig. 28 Oxygen dissociative pressure in iron oxide

The oxygen potential is calculated to be  $4.2 \times 10^{-17}$  atm for the C/ CO equilibrium and  $1.4 \times 10^{-11}$  atm for the Fe<sub>1</sub>O/Fe equilibrium. The CO partial pressure of the blow 1 slag is estimated to be  $4.2 \times 10^{-17}$ to  $1.4 \times 10^{-11}$  atm. The results calculated above are shown in **Fig. 28**. The oxygen potential of the blow 1 slag is sufficiently low. The dissociation reactions of oxygen in Fe<sub>2</sub>O<sub>3</sub>, Fe<sub>3</sub>O<sub>4</sub>, and FeO are each thought to proceed. From the difference between the dissociation pressure and the oxygen potential of the blow 1 slag, the dissociation reaction of Fe<sub>2</sub>O<sub>3</sub> is presumed to proceed most readily.

Ogawa and Tokumitsu<sup>19)</sup> observed the dissolution behavior of iron ore pellets (Fe<sub>2</sub>O<sub>3</sub>) in the molten slag from x-ray fluoroscopy images. They reported that the iron ore pellets were enveloped in oxygen gas, floated, dissolved on the slag surface, and decreased in the frequency of contact with the hot metal.

When the iron ore is compared with the dust agglomerate on the basis of the above discussion, the dissociation of oxygen occurs easily on the iron ore composed of almost only  $Fe_2O_3$ . The oxygen gas generated is estimated to have decreased the frequency of contact with the hot metal and to have decreased the reduction rate by impeding the mass transfer and heat transfer, consequently lowering the reduction degree. On the other hand, the dust agglomerate contains a large amount of FeO and produces little oxygen gas. It is also an agglomerate of very fine dust particles and thus can easily contact the hot metal or readily dissolve in the slag. As a result, the reduction reaction of the dust agglomerate is considered to have progressed faster than that of the iron ore.

## 4.4 Effect of improvement of reduction efficiency of iron oxide in BOF

With the measures for expanding the dust manufacturing capacity described in 3.1, we prioritized the use of fine BOF dust in TPC desiliconization and increased the use of the excess fine BOF dust by 1.0 kg/t from 4.3 kg/t in fiscal 2010 to 5.3 kg/t in 2014. This utilization of the dust agglomerate with a high reduction degree of 82% reduced the iron loss and reduced the T. Fe content discharged outside by 0.1 kg/t.

## 5. Effects of Expanding Recycling of Slag and Dust and Reducing Iron Loss

The effects of the initiatives taken to reduce the specific amount of slag discharged outside are summarized in **Fig. 29**. For a comparison of the effects, the results of fiscal 2014 were corrected by tapped hot metal Si×HMR=0.41% in fiscal 2010. The specific amount of slag discharged outside improved to 16 kg/t, by 7 kg/t by



Fig. 29 Decrease of amount of slag for out of the recycle system



Fig. 31 Comparison of reduction rate of each iron oxide

the expansion of TPC desiliconization, and by 3 kg/t by the expansion of slag recycling. **Figure 30** shows the effects of the initiatives taken to reduce the specific iron loss. The specific iron loss improved to 3 kg/t, by 2 kg/t by the expansion of TPC desiliconization, and by 0.5 kg/t by the expansion of slag recycling.

Figure 31 shows the reduction degree of the iron oxides. Figure 32 shows the effects of the initiatives taken to increase the specific amount of dust recycled. The specific amount of dust recycled increased to 7.4 kg/t for TPC desiliconization with a high iron oxide reduction degree and increased by 1.0 kg/t for BOF operation. To summarize the above results, the specific amount of iron loss was reduced 0.6 kg/t by the recycling of desiliconization dust and 0.1 kg/t by the use of dust agglomerate, or a total of 0.7 kg/t.



#### 6. Conclusions

The initiatives taken to reduce the iron loss from the viewpoint of recycling the slag and dust are summarized as follows:

- Centering on decreasing the amount of formed slag by increasing the amount of the blow 2 slag recycled and by increasing TPC desiliconization, the specific amount of slag discharged outside was reduced 16 kg/t in fiscal 2014 as compared with fiscal 2010. Furthermore, the specific amount of iron loss due to the outside discharge of slag was reduced 3 kg/t.
- 2) The reduction degree of the iron oxides in the MURC blow 1 and TPC desiliconization was calculated. The reduction degree of the iron oxides was improved by using the iron oxides in the order of: TPC desiliconization dust (92% reduction degree), blow 1 agglomerate (82% reduction degree), and blow 1 iron ore (58% reduction degree). The valuable Fe in the blow 2 slag was also recovered and recycled to TPC desiliconization.
- 3) Concerning the iron ore that is often not completely reduced in the BOF and results in iron loss, the specific amount of this iron loss was reduced 0.6 kg/t by recycling the desiliconization dust to TPC desiliconization (powder injection method) and 0.1 kg/t by using the dust agglomerate, or a total of 0.7 kg/t.

To summarize the above results, the specific amount of iron loss was reduced 0.6 kg/t by the recycling of desiliconization dust and 0.1 kg/t by the use of dust agglomerate, or a total of 0.7 kg/t.

#### Appendix

The equations used to calculate the T.Fe content of the TPC desiliconization slag and the amount of the TPC desiliconization slag are given below.

- T.Fe content of TPC desiliconization slag
- = Amount of TPC desiliconization slag  $\times$  T.Fe content of TPC desiliconization slag (%) (14)
- Amount of TPC desiliconization slag
- = Amount of TPC desiliconization slag + Amount of BF slag
- Amount of TPC desiliconization slag
- = Amount of quicklime charged  $\times$  Grade + Amount of SiO<sub>2</sub> formed + Amount of blow 2 slag  $\times$  Residual proportion (16)

where the amount of the BF slag and the proportion of the blow 2 slag remaining in the desiliconization slag (residual proportion) are both assumed to be constant.

The reduction degree of the iron ore and the dust agglomerate are defined by the following equations in the same way as the reduction degree of the iron oxide in TPC desiliconization. The calculations are made by each equation from the analysis values of CaO, SiO<sub>2</sub>, and T. Fe in the blow 1 slag during intermediate deslagging. • Reduction degree of iron ore

- = T.Fe content of reduced iron ore/T.Fe content of iron ore charged (17)
- T.Fe content of reduced iron ore
- = T.Fe content of charged iron oxide T.Fe content of unreduced iron ore (18)
- T.Fe content of iron ore charged
- = Amount of iron ore charged  $\times$  T.Fe content of iron ore (19)
- •T.Fe content of unreduced iron oxide
- = T.Fe content of blow1 slag T.Fe content of blow1 slag (Amount of iron ore charged: 0 kg/t) (20)
- •T.Fe content of blow 1 slag
- = Amount of slag in blow 1 furnace  $\times$  T.Fe content of blow 1 slag (%) (21)
- •Amount of slag in blow furnace
- = Amount of CaO charged in blow1 furnace/CaO content of blow1 slag (%) (22)
- Reduction degree of agglomerate
- = T.Fe content of reduced agglomerate/T.Fe content of agglomerate charged (23)
- T.Fe content of agglomerate = T.Fe content of agglomerate charged - T.Fe content of unreduced agglomerate (24)
- T.Fe content of agglomerate charged = Amount of agglomerate charged × T.Fe content of agglomerate (25)
- T.Fe content of unreduced agglomerate = T.Fe content of blow 1 slag - T.Fe content of blow 1 slag (Amount of agglomerate charged: 0 kg/t) (26)

#### References

- 1) Oita Works, Nippon Steel: 127th Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2002 (for members only)
- Oita Works, Nippon Steel: 131st Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2004 (for members only)
- Oita Works, Nippon Steel: 145th Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2011 (for members only)
- Oita Works, Nippon Steel: 136th Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2007 (for members only)
- Oita Works, Nippon Steel: 143rd Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2010 (for members only)
- Oita Works, Nippon Steel & Sumitomo Metal: 151st Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 2014 (for members only)
- 7) Oita Works, Nippon Steel: 119th Meeting of Steelmaking Committee of the Iron and Steel Institute of Japan, 1999 (for members only)
- Hara, S., Ogino, K.: Tetsu-to-Hagané. 76, 360 (1990)
   Kawauchi, Y., Maede, H., Kamisaka, E., Satoh, S., Inoue, T., Naki, M.: Tetsu-to-Hagané. 69, 1730 (1983)
- 10) Kaneko, T., Matsuzaki, T. : Tetsu-to-Hagané. 78, 1690 (1992)
- 11) Ogawa, Y., Yano, M., Kitamura, S., Hirata, H.: Tetsu-to-Hagané. 87, 21 (2001)
- 12) Shimomura, Y.: Tetsu-to-Hagané. 78, 509 (1992)
- 13) Nagasaka, T., Ban-ya, S.: Tetsu-to-Hagané. 78, 1753 (1992)
- 14) Tsukihashi, F., Amatatsu, M., Soma, T.: Tetsu-to-Hagané. 68, 1880 (1982)
- Ogino, K.: High Temperature Surface Chemistry (Last vol.). Tokyo, AGNE Gijutsu Center Inc., 2008, p.23 (in Japanese)
- 6) Ohtani, M.: Metallurgical Thermodynamics for Steelmaking. Tokyo, Nikkan Kogyo Shimbun, Ltd., 1971, p. 154 (in Japanese)
- 17) The 19th Committee on Steelmaking: Steelmaking Data Sourcebook. The Japan Soc. for the Promotion of Science, Gordon and Breach Science Publishers, New York, 1988
- Barin, T., Knacke, O.: Thermochemical Properties of Inorganic Substances. Supplement Vol. 1, 1973
- 19) Ogawa, Y., Tokumitsu, N.: Tetsu-to-Hagané. 87, 14 (2001)

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