NIPPON STEEL TECHNICAL REPORT No. 124 SEPTEMBER 2020

Technology

UDC 669 . 184 . 28

Reduction of BOF Slag Emission at Hirohata Works[*1]

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Abstract

Hirohata Works has been producing hot metal using recycled raw materials since 1993, but instead of scrap as the main raw material, the proportion of hot briquetted iron using dust as the raw material or bullion is increasing. However, the use of raw materials containing a large amount of impurities has increased the amount of hot metal phosphorus and the demerits in the decarburization furnace (increased CaO, increased slag, decreased iron yield). This study reports the improvement of these disadvantages through the recycling of converter slag and improvement of its utilization. Furthermore, the effect of dust reduction by promoting slag forming was also obtained.

1. Introduction

The steelmaking process of Hirohata Works of Nippon Steel Corporation is of the resource circulation type, and produces hot metal (molten iron) by melting steel scrap and/or reduced iron by the Scrap Melting Process (SMP) method. In the past, conventionally, steel scrap was used mainly for the SMP method. Recently, however, Hot Briquetted Iron (HBI: hot granulated reduced iron) and bullion that contains a high degree of impurities are increasing. HBI are briquettes of the fine grain iron source[*2] mixed with carbon material and binder, and then hot-granulated and reduced in a rotary hearth furnace (RHF). Use of the reduced iron and bullion in a greater quantity is planned for the future. On the other hand, since the hot metal phosphorus content increases by using these raw materials, the increase of slag volume and the deterioration of BOF yield have become problematic. Therefore, as countermeasures to such problems, improvement of the BOF slag recycling and utilization technology has been developed, the result of is reported hereunder.

2. Iron Source Manufacturing Process and BOF Process at Hirohata Works

2.1 Outline of the steelmaking process at Hirohata Works

Figure 1 shows the steelmaking process at Hirohata Works. Hot metal is produced through the cold iron source melting process that melts such iron source as steel scrap, HBI, and so forth by the SMP furnace. Then, molten steel is produced by applying injection desulphurization treatment and BOF decarburization to all hot metal.

2.2 Operation flow in SMP process and its features

The SMP process is a cold iron source melting process that utilizes a converter type furnace and exploits the heat of the previous hot metal that partly remains in-furnace successively for the next heat operation.[1)] The iron source such as the steel scrap charged through a top chute and the HBI continuously charged from the furnace top are melted by the heat sources such as of top-blown oxygen and bottom-blown pulverized coal. After melting is completed, the hot metal is tapped, leaving in-furnace a portion of the hot metal as the pilot heat source for the next heat, and the SMP furnace is then prepared for the subsequent heat. This operation is repeated successively. In the SMP method, as hot metal desulphurization treatment is set up in the subsequent process, any input of [S] is tolerated and therefore, the iron source containing a high sulfur content that is not tolerated in BOF is also usable. Comparisons of the components and the temperature between those of the blast furnace (BF) hot metal and those of the SMP method hot metal are shown in **Table 1**. As compared with BF hot metal, the tapping temperature and the carbon content are lower, and the sulfur content is higher. In addition, as melting is conducted by oxygen blowing, silicon is oxidized entirely in the SMP furnace and does not remain in hot metal at tapping.

[*1] Reproduced from the Iron and Steel Institute of Japan 153rd Steelmaking Subcommittee presentation paper

[*2] Blast furnace and steelmaking dust generated in-house and outside the company

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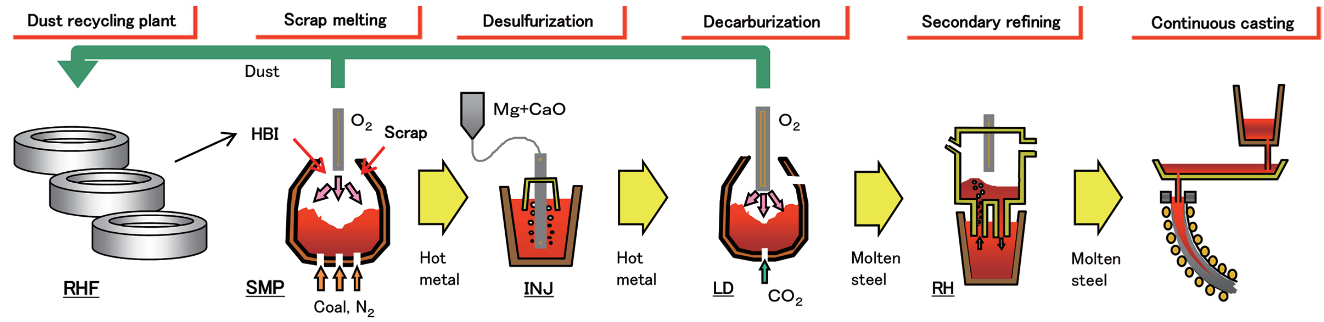

Fig. 1 Steel manufacturing process at Hirohata Works

Table 1 Comparison of hot metal between SMP and blast furnace

	Tap temp. (°C)	[C] (%)	[Si] (%)	[Mn] (%)	[P] (%)	[S] (%)
SMP	1390	4.2	0	0.25	0.07	0.09
BF	1500	4.6	0.5	0.3	0.12	0.02

Table 2 Specification of BOF at Hirohata Works

Bottom blow	LD-CB
Top O_2 blow	Max 25000 Nm^3/h
Heat size	100 t

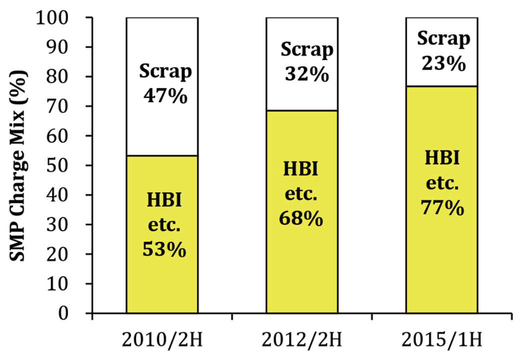

Fig. 2 Charge mix of SMP

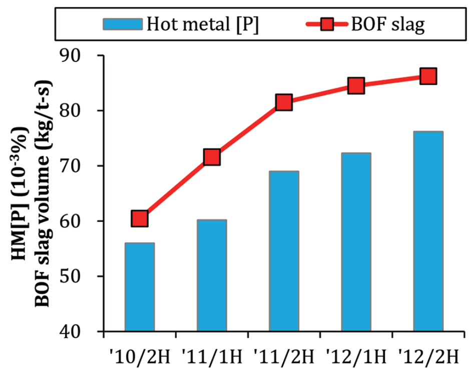

Fig. 3 Relation between hot metal [P] and BOF slag volume

2.3 BOF process at Hirohata

At the Hirohata steelmaking plant, one BOF is installed for two SMP furnaces. **Table 2** shows the main specification of the BOF. CO_2 or N_2 is used as the bottom blowing gas. As SMP hot metal does not contain silicone, desiliconization treatment is not required and furthermore, since the production of steel of equal to or less than 0.01% ([P]≤0.01%) is not scheduled, hot metal pretreatment other than desulphurization treatment is not conducted, and dephosphorization treatment is conducted only in the decarburizing furnace.

3. Transition of SMP Material Mix and Influence on BOF

3.1 Transition of SMP material mix

Figure 2 shows the SMP material mixes in the second half of 2010, the second half of 2012, and the first half of 2015. Along with the increase of the installation of RHF, the share of HBI has increased. In addition, the share of bullion has also increased in parallel. The cost of these materials is lower than that of scrap, and Hirohata Works is planning to reduce the hot metal cost by increasing the use of reduced iron and bullion.

3.2 Change of hot metal compositions due to change in SMP material mix

Both HBI and bullion increasing in the charge mix contain 5–10 times more phosphorous than that of steel scrap. In **Fig. 3**, the transitions of hot metal [P] and the slag volume from the first half of 2010 to the second half of 2012 are shown. Hot metal [P] increased by 1.3 times during the period and along with the increase, the slag volume also increased by 1.4 times (60 kg/t-s to 86 kg/t-s).

4. Technical Development Principle Based on SMP Hot Metal Characteristics

To counter the increase of the BOF slag volume and the deterioration of yield that emerged therewith, slag recycling was promoted. This study reports the promotion of hot recycling in which slag remains in the SMP furnace and the promotion of cold recycling in which selected slag is recycled in the cold state.

4.1 Endeavour to promote BOF slag recycling

4.1.1 Concept of utilization of hot recycling and cold recycling

The characteristics of hot recycling and cold recycling are shown in **Table 3**. The hot recycling is thermally advantageous and further advantageous in that slag is used without such treatment as crushing. On the other hand, the cold recycling has the merit of freedom in selecting the type of slag and the timing of reuse. Upon conducting BOF slag recycling, the effect of these characteristics was maximized.

4.1.2 Maximization of the effects of hot recycling and cold recycling

Table 4 shows the ratio, characteristics, and the recycling procedure with respect to the respective steel grade produced. Since the

Hirohata steelmaking plant is not equipped with a dephosphorization pretreatment process, slag needs to be effectively recycled in the decarburization furnace. As Table 4 shows, the higher the upper standard limit of phosphorus of a steel grade, the higher the (P_2O_5)/(CaO) of discharged slag. Namely, slag is to be used toward the steel grade ultimately having the highest standard phosphorus upper limit and then discharged. Based on this, slag recycling was promoted from the following viewpoint.

Hot recycling ①

Hot recycling from a steel grade with a lower upper standard limit of phosphorus to a steel grade having a higher upper standard limit of phosphorus (only between casts)

Hot recycling ②

Hot recycling within a steel grade with a high upper standard limit of phosphorus

Cold recycling

Low manganese steel slag that provides a large dephosphorization capability reserve is selectively recovered and reused for cold recycling.

For low manganese steel, in order to reduce the manganese content, excessive slag is produced from the viewpoint of dephosphorization. This slag contains rich T.Fe and the collection and reuse of the slag yield large effects of reducing the sub-raw materials and the recovery of iron.

4.1.3 Hot recycling

(1) Promotion of recycling to steels having higher upper limit phosphorus content

Figure 4 shows the relationship between the upper standard limit of phosphorus [P] and the actual average phosphorus content of products [P]. The higher the upper standard limit [P], the larger the difference between the upper standard limit value [P] and the actual value [P] becomes. This is due to the fact that although the slag volume is determined only by the amount of charged sub-raw material since SMP hot metal does not contain silicon, the lower limit slag volume is set from the viewpoint of providing appropriate cover slag and furnace protection. Therefore, excessive slag is formed from the sole viewpoint of dephosphorization. Steel grades with an upper limit phosphorus of 0.025% or above belong to this category. **Figure 5** shows the production mix of phosphorus-bearing steel with respect to the upper standard limit of phosphorus [P]. The mix of the steel grades with a phosphorus content of 0.025% or above having a high tolerance for phosphorus content exceeds 50% inclusive of the share of phosphorus-added steel. Hot recycling was applied to the steel grades of this category.

(2) Application of hot recycling and the effect thereof

Hot recycling applied to the abovementioned steel grades was successfully expanded and presently, the application ratio of hot recycling as to the entire production has reached 73% with the recycled hot slag of 8.1 kg/t-s (actual result between January and March in 2015). In **Figs. 6, 7**, the comparisons of newly charged CaO and the bullion discharge per unit weight of steel during slag-off before and after the application of hot recycling operation are shown, respectively. As a result, newly charged CaO was reduced by 13% as compared with before. Furthermore, along with the decrease of the full slag-off ratio from the furnace, the amount of bullion discharged

Table 3 Characteristics of slag hot recycle and cold recycle

	Hot recycle	Cold recycle
Method	To keep previous heat slag in BOF and to use in the next heat blowing	To collect off slag from BOF and to use the crashed slag as flux in BOF
Merit & demerit	◆ Merit Less heat loss ◆ Demerit Only previous heat slag can be used	◆ Merit Variety of slag can be used selectively ◆ Demerit Heat loss
Point	Increase of recycle ratio except low P heat	Selective recycle of slag from low Mn heat

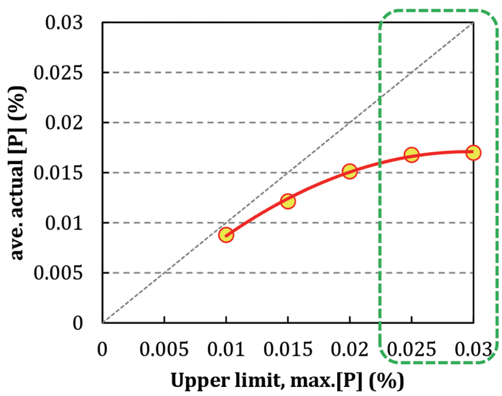

Fig. 4 Relation of phosphorus between upper limit (max.[P]) and actual

Table 4 Schematic view of slag recycle

Steel grade	Ratio	$(P_2O_5)/(CaO)$		Characteristic	Hot recycle ①	Hot recycle ②	Cold recycle
Phosphorus containing	10%	0.060	High	–			
High phosphorous Max.[P]≤0.025, 0.030%	44%	0.059		Margin for input P: High Max.[P] >> Actual [P]			
Medium phosphorous Max.[P]≤0.020%	28%	0.050		Margin for input P: Medium Max.[P] > Actual [P]			
Low phosphorous Max.[P]≤0.015%	3%	0.046		Max.[P] ≈ Actual [P] Slag: De-P capacity remaining			
Low manganese containing	16%	0.038	Low	Slag: De-P capacity remaining Slag: High T-Fe			

was improved significantly by 82%.

(3) Consideration on improvement in newly charged CaO

Expression (1) is reported as an empirical expression that denotes the dependency of the phosphorus distribution ratio between slag and molten steel on slag composition.[2)]

$$\log\{(P)/[P](T.Fe)^{5/2}\} = 0.0720\{(\%CaO)+0.3(\%MgO)+0.6(\%P_2O_5)+0.2(MnO)+1.2(\%CaF_2)-0.5(Al_2O_3)\}+11570/T-10.52$$

T: Temperature (K) (1)

Expression (1) above is called Healy's expression.[3)] **Figure 8** shows the relationship between the phosphorus distribution ratio calculated by this expression and the actual phosphorus distribution ratio. By applying hot recycling, the gap between the calculated result and the actual result is decreasing, which is considered to be attributed to the result of the decrease of CaO that is not formed as slag due to the repeated use of slag. Additionally, in **Fig. 9**, the relationship between the charging basicity and the actual basicity is shown. This figure shows that the gap between the charging basicity and the actual basicity is decreased by applying hot recycling. This result confirms that the amount of undissolved CaO decreased even after blowing (**Fig. 10**).

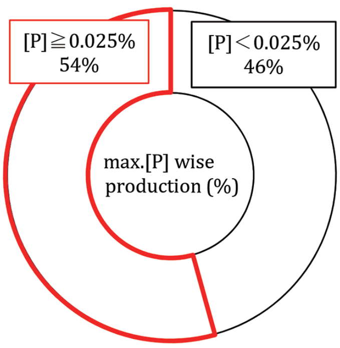

Fig. 5 Production structure of phosphorus containing steel

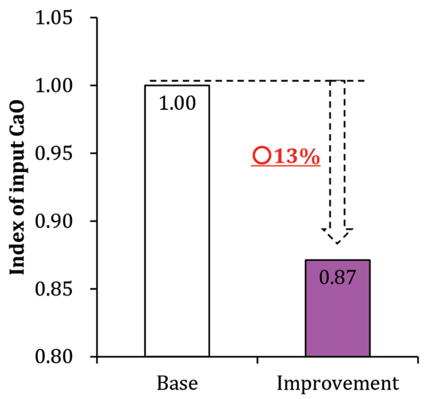

Fig. 6 Decrease of CaO by slag hot recycle

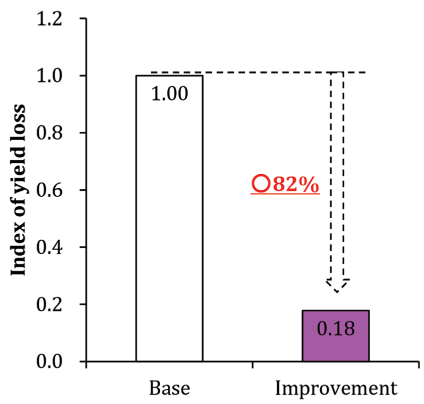

Fig. 7 Decrease of yield loss during slag-off

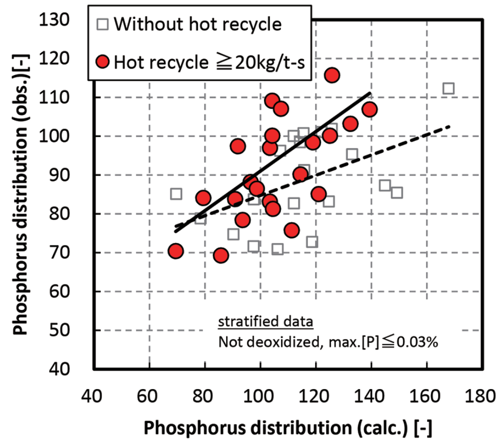

Fig. 8 Influence of slag hot recycle on (P)/[P] ratio

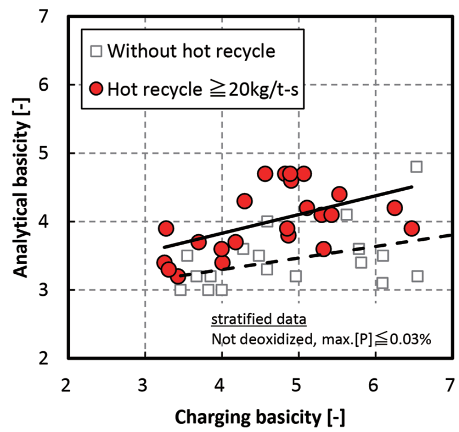

Fig. 9 Relation between charging basicity and analytical basicity

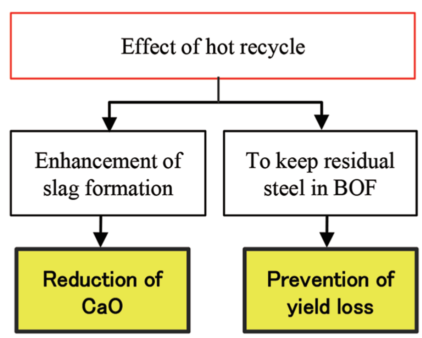

Fig. 10 Effect of slag hot recycle

4.1.4 Cold recycling of low manganese steel slag

(1) Result of sub-raw material reducing test

The low manganese steel slag was collected selectively and the cold slag recycling test was conducted. Cold slag of 10 kg/t-s was charged immediately after the start of blowing. To conduct tests under the same condition, the subject steel grade was limited only to steels with a high upper limit phosphorus content (upper limit [P]=0.03%).

Figure 11 shows the relationship between the index of CaO input and blow end point phosphorus content [P]. In addition to the effect of cold recycling on the reduction of the CaO input, its effect of decreasing the end point [P] is also recognized. This is considered to be attributed to the enhanced slag formation efficiency of CaO. In **Fig. 12**, the relationship between the charging basicity defined as CaO/SiO_2 and the actual basicity is shown. As compared with the case of without cold recycling (0 kg/t-s), in the case of cold recycling of 10 kg/t-s, the gap between the charging basicity and the actual basicity decreased, and CaO is effectively formed as slag. The ratio of CaO formed as slag vs. charging T.CaO in the case of cold charging of 10 kg/t-s was improved to as high as 93% from 82% of the case without recycling. This behavior is the same as that of hot recycling. In **Fig. 13**, likewise the case of hot recycling, the relationship between the actual phosphorus distribution ratio and the phosphorus distribution ratio calculated by Expression (1) is shown. In this case too, the gap between the calculated values and the actual values decreased, which is also considered to be attributed to the effectively formed slag from CaO.

(2) Result of recovery of iron content from low manganese steel slag

Figure 14 shows the relationship between the blow end point [C] and T.Fe obtained from the test. There is no difference in T.Fe of the end point slag with respect to the cases with or without cold recycling. This indicates that the iron content of the recycled slag is reduced during blowing and recovered.

(3) Dust generation reduction effect of cold recycling

Figure 15 shows the average sound level during the period of blowing from the early stage to intermediate stage (5–11 min after the start of blowing) for the cases without cold recycling (0 kg/t-s) and with cold recycling (10 kg/t-s). The slag forming progresses further and the slag height is higher at the lower sound level. The sound level has clearly decreased by charging cold slag of 10 kg/t-s. As shown similarly in the results in Figs. 12, 13, the progress of slag formation by cold recycling with charging of 10 kg/t-s is manifested. There is a possibility that, along with the progress of the slag forming, the dust generation is suppressed by the liquefied slag covering the molten steel surface. Then, the influence of the slag recycling on the generation of dust was studied.

The test condition is shown in **Table 5**. The test was conducted on the following three conditions: without slag recycling (base), hot

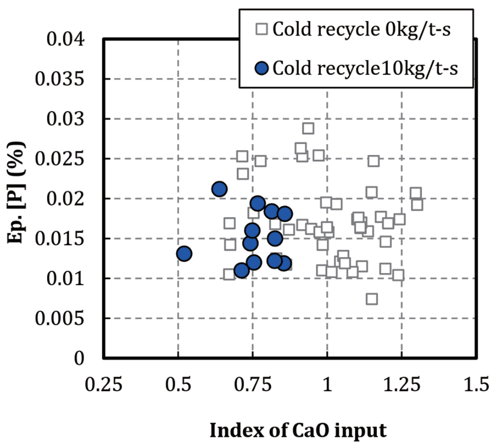

Fig. 11 Influence of slag cold recycle on [P] at blowing end point

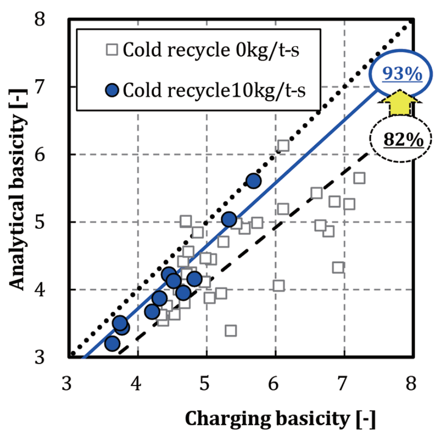

Fig. 12 Relation between charging basicity and analytical basicity

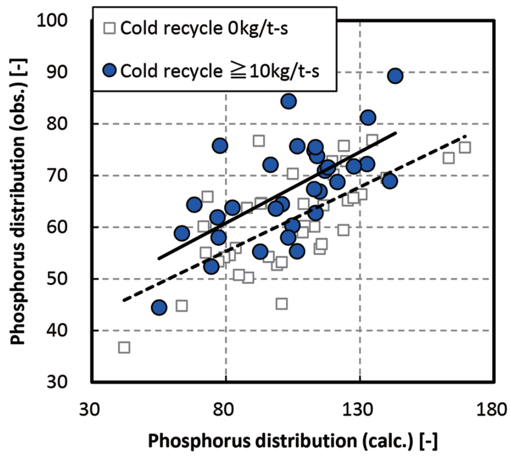

Fig. 13 Influence of slag cold recycle on (P)/[P] ratio

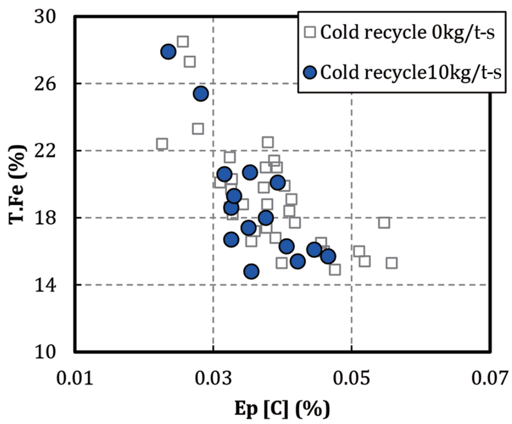

Fig. 14 Relation between blowing end point carbon and iron content in slag

recycling with 10 kg/t-s, and cold recycling with 10 kg/t-s. The test was conducted regardless of the order of the recycling conditions under a common condition with respect to in-furnace slag volume, lance height, oxygen supply rate, bottom gas blow rate, and sub-raw material charging timing. The amount of dust generated was measured by sampling the dust-catching water at two-minute intervals.

Figure 16 shows the transitions of the dust generation rate in the test conditions at ① through to ③. A difference in the dust generation rate is observed in the early stage of blowing (from start to 10 min after) and that dust generation is suppressed only in cold recycling. In **Fig. 17**, the relationship between the sound level and the dust generation rate in the time region between 5–10 min after start of blowing is shown. At the low sound level, the dust generation rate tends to be suppressed and the sound level is situated at a low level in cold recycling. This indicates that, by applying cold recycling, slag formation is promoted more readily in the early stage of blowing and the generation of dust is reduced as the cover slag is formed early. In **Fig. 18**, the index of dust generation throughout the entire blowing period is shown. As a result, when cold recycling is applied, the dust generation is reduced by 15–20%.

(4) Consideration of the early stage slag formation promoted by cold recycling

The following two aspects were considered as factors that explain the superior slag forming capability of cold recycling as compared with that of hot recycling. ① Primary slag composition and the influence of the change of the slag composition when slag is solidified, and ② Influence of the in-furnace slag existing position.

When applying hot recycling, slag is solidified by charging cooling material to prevent slag blow out when charging scrap and hot metal. **Figure 19** shows the result of the calculation by SOLGASMIX of the liquid phase fraction with respect to low manganese steel blow end point slag composition, average slag blow end point

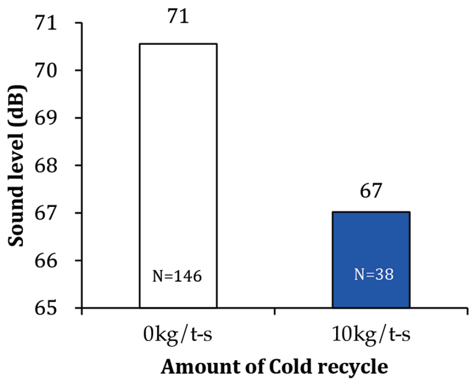

Fig. 15 Influence of slag cold recycle on sound level

Table 5 Blowing condition for dust measurement

Recycle		Condition
①	Base	Without hot recycle and cold recycle
②	HOT	Hot recycle 10 kg/t-s
③	COLD	10 kg/t-s of cold slag into furnace at blowing start

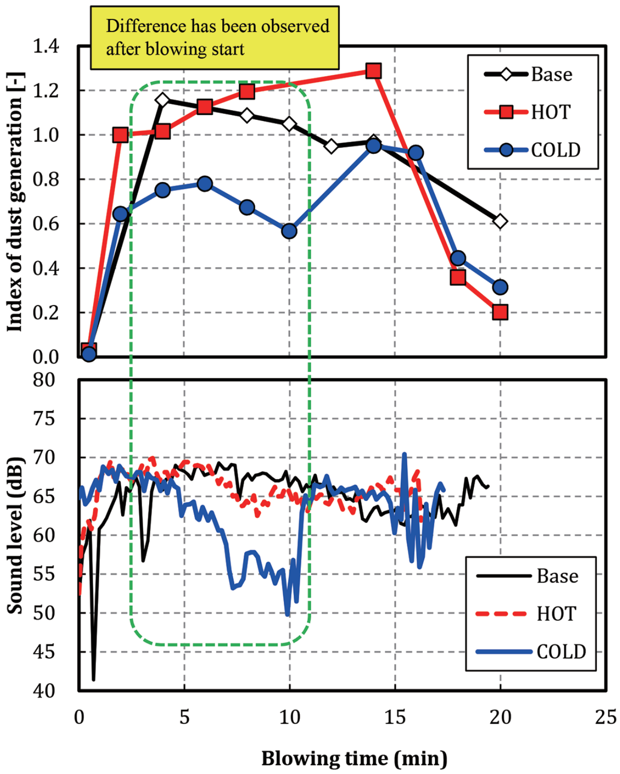

Fig. 16 Results of dust generation measurement

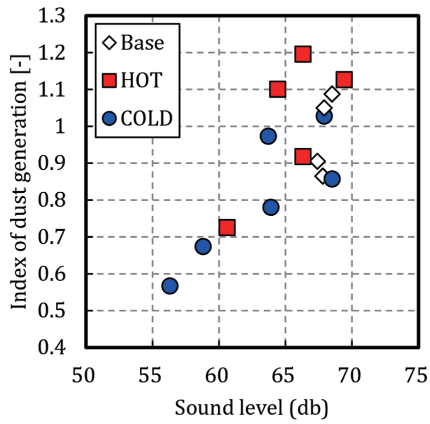

Fig. 17 Relation between sound level and dust generation

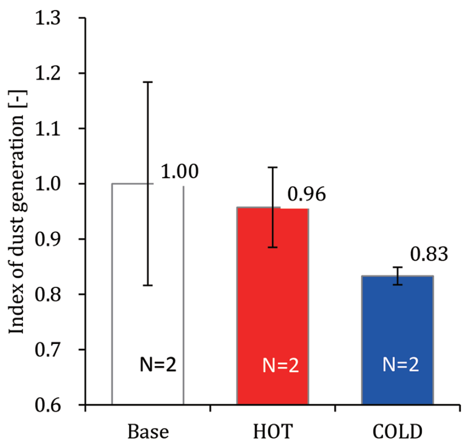

Fig. 18 Influence of slag recycle on dust generation

composition, and the average slag composition after solidification. With respect to the solidified slag, to be under the same condition as the abovementioned test, the calculation was conducted based on the mixed compositions of the in-furnace hot slag (average blow end slag) and the dolomite charged at a rate of 5 kg/t-s per 10 kg/t-s of the hot slag. As compared with the blow end average slag solidified, the liquid phase fraction of the cold slag of the low manganese steel used in the test is higher by about 30% at any temperature and considered to be advantageous in slag forming.

Furthermore, as a cause of difference in solubility due to the difference in existing positions, hot slag is solidified while remaining in-furnace and adheres to the furnace wall and the furnace bottom, under which state scrap and hot metal are charged and blowing is started. Therefore, the hot slag is melted by the hot bath heat. The bath temperature in the early stage of blowing is about 1350–1450°C. On the other hand, cold slag is charged from the top after scrap and hot metal are charged, and floats on the bath surface. Accordingly, the slag opts to stay close to the fire spots that are considered to be at 2000–2600°C,[4] and therefore, slag melting is considered to progress more readily under such a high temperature from the early stage of blowing. Namely, in the early stage of blowing, differently from the case of hot slag that exists in the region as shown by region A in Fig. 19, cold slag is considered to exist in region B. Accordingly, it is considered that the slag formation in the early stage is promoted in cold recycling and a significant reduction in dust is obtained.

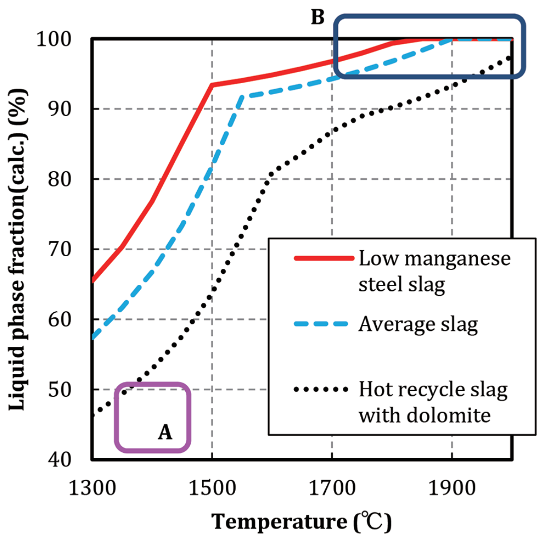

Fig. 19 Calculated liquid phase fraction of slag

5. Study on Operation Utilizing Hot Recycling and Cold Recycling

5.1 All recycled slag use operation of phosphorus-bearing steel

After conducting hot recycling, slag needs to be solidified to suppress the slag blow out at the time of charging scrap and hot metal. In the operation before the establishment of cold recycling, slag was solidified by using lime and/or dolomite after hot recycling. By applying cold recycling, slag solidification could be secured by cold slag, and implementation of all recycled slag use operation with no newly generated slag has been realized (**Figs. 20, 21**). This operation mode exploits to the extent possible the characteristics of the SMP hot metal that does not contain silicon.

5.2 Verification of sub-raw material reduction effect

By applying the abovementioned operation to the phosphorus-bearing steel, effects such as the reduction of sub-raw material, squeezing of heat tolerance, and the reduction of alloy metals are expected. A test was conducted with respect to phosphorus-bearing steel. The previous charge slag was wholly hot-recycled and solidified by charging cold slag of 15 kg/t-s. During blowing, only dolomite and iron ore were charged for teeming and temperature adjustment. In **Figs. 22, 23**, the actual values of newly charged CaO and hot metal ratio during the test are shown. Except dolomite charged for absorbing nitrogen, operation without charging new CaO could be established. Furthermore, by reducing the amount of charging of sub-raw materials, heat tolerance and the effect of reducing the hot metal ratio could be obtained.

5.3 Verification of alloy metal reduction effect

Figure 24 shows the mass balance of phosphorus during the series of tests. By recycling 100% of hot slag, the total content of the

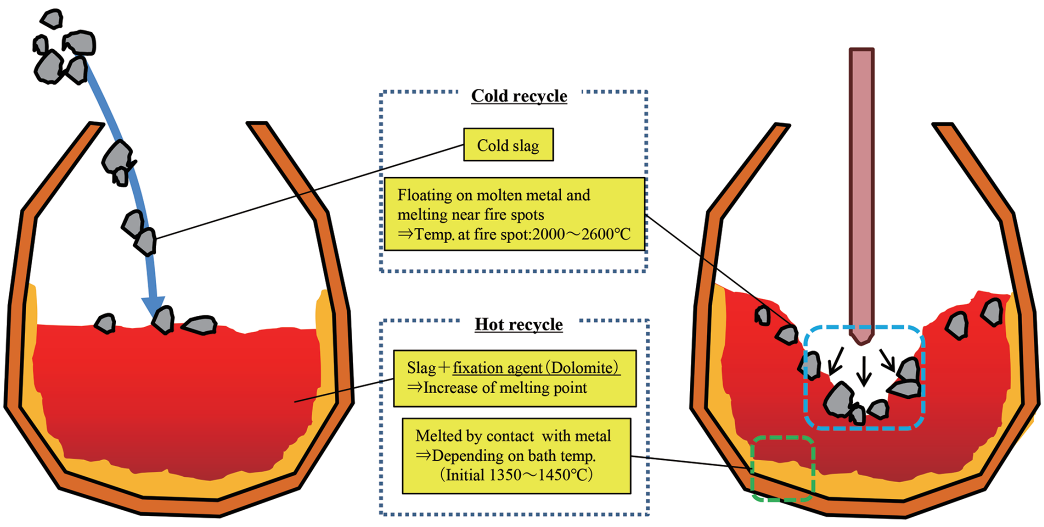

Fig. 20 Schematic view of melting phenomena of recycled slag

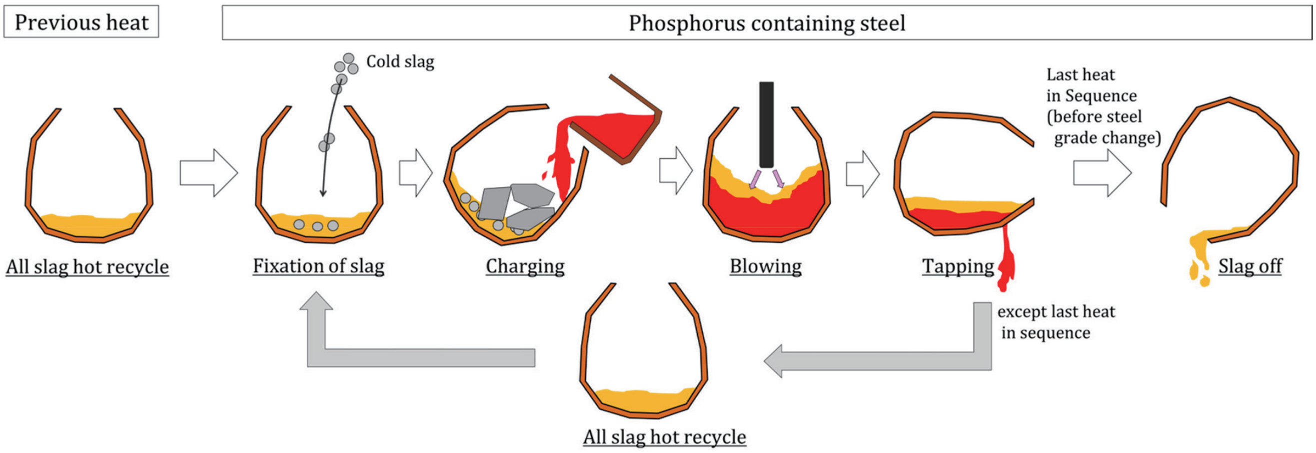

Fig. 21 Schematic view of all slag hot recycle operation

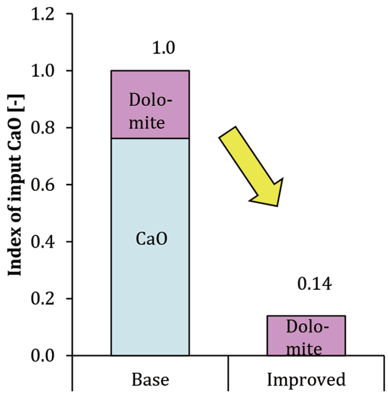

Fig. 22 Improvement of slag hot recycle for phosphorus containing steel

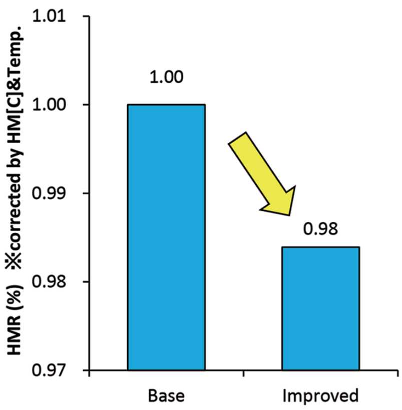

Fig. 23 Improvement of hot metal ratio for phosphorus containing steel

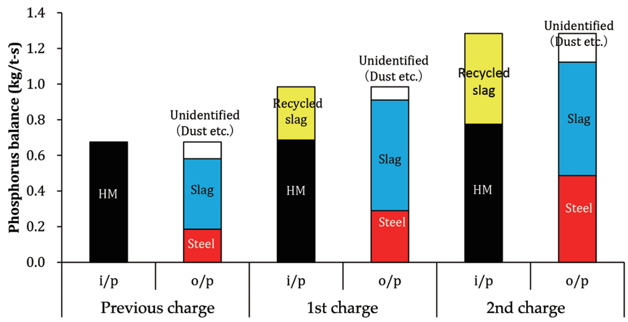

Fig. 24 Mass balance of phosphorus during all slag hot recycle operation

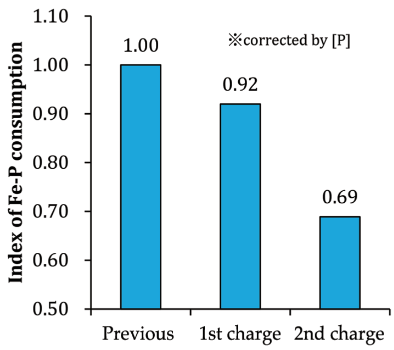

Fig. 25 Influence of all slag hot recycle on consumption of phosphorus alloy

input phosphorus increases stepwise. On the other hand, regarding the output also, it has become clear that the phosphorus content in molten steel increases and the end point [P] increases. As a result, as shown in **Fig. 25**, the actual reduction of the amount of Fe-P alloy metal was confirmed. This is the result of a test conducted for two consecutive heats. It is considered that the effect will grow larger as the number of consecutive all slag recycle operation increases.

The slag volume of the previous heat was adjusted so that the in-furnace slag volume in the test becomes equal to that of the actual operation. To enhance the blow end point [P], another way is to reduce the slag volume. However, if the slag volume is too small, there is concern that ① increase of dust generation and nitrogen absorption of steel due to shortage of cover slag, and ② deterioration of the furnace protecting function will occur. The lower limit slag volume described in 4.1.3 (1) was set on the operation field basis and we will hereafter investigate the influence of slag volume minutely and study the optimum slag volume.

6. Effect Provided by Implementation of Reported Measures

Both the hot recycling (application ratio 73%, 8.1 kg/t-s) and the cold recycling wherein slag is recovered selectively (average 7 kg/

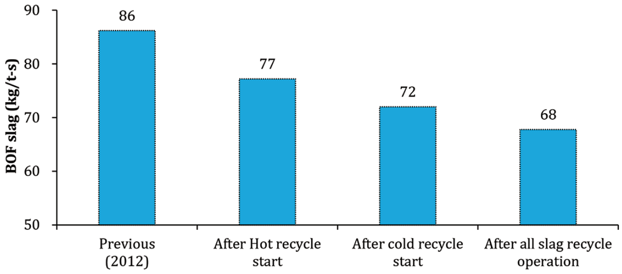

Fig. 26 Improvement of BOF slag generation by development of slag recycle operation

t-s for all steel grades) have already been applied to the actual operation and both are enjoying improved operation. In **Fig. 26**, the effect of improving slag generation by the abovementioned measures is shown. By implementing the respective measures, the BOF slag generation could be reduced by 21% (86 kg/t-s→68 kg/t-s) from the second half of 2012, the year before the start of the measures.

7. Conclusion

As a result of investigating BOF slag recycling targeting the reduction of BOF slag volume and improvement in yield, the following findings were obtained.

- As a result of implementation of hot recycling and cold recycling, CaO utilization efficiency is improved.
- Slag formation is promoted by cold recycling, and in particular, the dust generation rate in the early stage of blowing can be reduced.
- By the maximized utilization of recycled slag, for phosphorus-bearing steel production, operation without using lime at all is realized.
- In all recycled slag use operation for phosphorus-bearing steel, an alloy metal reduction effect by the increased blow end point [P] is obtained.

References

1) Ohnuki, K., Umezawa, K., Hiraoka, T., Matsumoto, N., Inoue, T.: Development of Steel Scrap Melting Process, Shinnittetsu Giho. (351), 47 (1994)
2) Suito, H., Inoue, R.: ISIJ Int. 35, 258 (1995)
3) Healy, G. W.: J. Iron Steel Inst. 153, 115 (1949)
4) Kawakami, K.: Tetsu-to-Hagané. 74 (5), 79–86 (1988)


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