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Quality Improvement of Sintered Ore in Relation to Blast Furnace Operation

Kenichi HIGUCHI*1 Yasushi TAKAMOTO*1
Takashi ORIMOTO*1 Takehiko SATO*2
Fumio KOIZUMI*2 Kazuyuki SHINAGAWA*3
Hiroyuki FURUTA*3

Abstract

High productivity operation of a blast furnace requires enhancing reducibility and improving reduction behavior at high temperatures of sintered ore. Analysis results of sintered ores with extensive ranges of chemical composition showed that reduction behavior of sinter depended on their chemistry and pore structure as a result of changes in the amount of liquid phase, viscosity and smelting-reduction rate of formed slag containing 'FeO'. Sinter with High Fe content, proper basicity range (1.5-2.0), low Al_2O_3 content and fine pores below 15 μ m in size had superior reduction behavior. Finally, sinter with low SiO_2, low MgO and low Al_2O_3 has been developed and manufactured in all works in Nippon Steel, resulting in improvement of blast furnace operation.

1. Introduction

Over the last 20 years Nippon Steel Corporation has reduced the number of its blast furnaces, and as a result, the company produces pig iron mostly on large blast furnaces at high productivity coefficients. What is more, owing to the increase in the injection amount of pulverized coal, the ore/coke ratio of furnace burden has increased, resulting in a relative decrease in the charging amount of coke, which plays an important role in maintaining good permeability of a blast furnace. To sustain stable furnace operation under such a difficult condition, the company has concentrated efforts on the improvement of the quality of sinter, especially reducibility and high-temperature reduction properties (the softening, melting and dripping behavior), besides securing sufficient supply of sinter.

This paper presents Nippon Steel's activities for clarifying the factors that determine the reducibility and high-temperature reduction properties of sintered ore, introduces some examples of blast furnace operation improvement through optimization of the composition and structure of sintered ore, and points out what remains to be done for further improvement.

2. Factors Determining High-temperature Reduction Behavior of Sintered Ore[1)]

2.1 Relationship between chemical composition and high-temperature reduction behavior of sintered ore

Fig. 1 shows the relationship between the dripping temperature Td (the temperature at the time when a dripping detector detects the first dripping of iron ore from a graphite crucible) and the composition of sintered ores and pellets. Here, a loaded-softening-melting tester[2)] was used under an adiabatic condition, and the sintered ores were those prepared using test pots. The Td tended to fall as T.Fe increased. Moreover, it was lowest in the range of basicity (CaO/SiO_2, or C/S) from 1.0 to 1.1. The influence of Al_2O_3 on the Td changed depending on the basicity: whereas the Td rose as the Al_2O_3 content increased when the basicity was low (1.6 or less), it decreased as the Al_2O_3 content increased when the basicity was high. On the other hand, the Td tended to fall as the MgO content increased, and this tendency was more conspicuous when the basicity was high.

The liquidus line temperature of $CaO-SiO_2-Al_2O_3-FeO$ slag becomes higher in a basicity range of 1.0 or more, and the ratio of the

*1 Environment & Process Technology Center
*2 Hokkai Iron & Coke Corporation
*3 Yawata Works

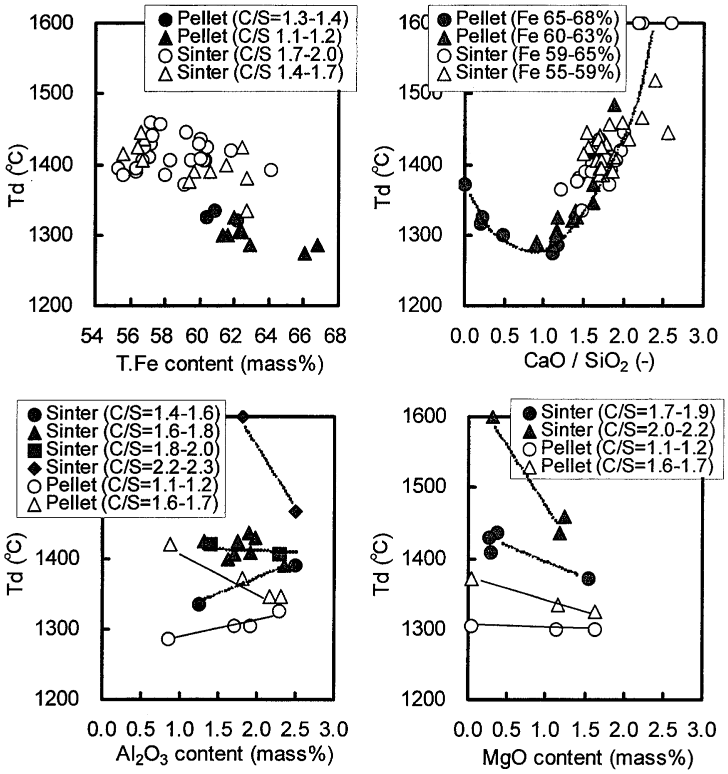

Fig. 1 Influence of chemical composition on dripping temperature

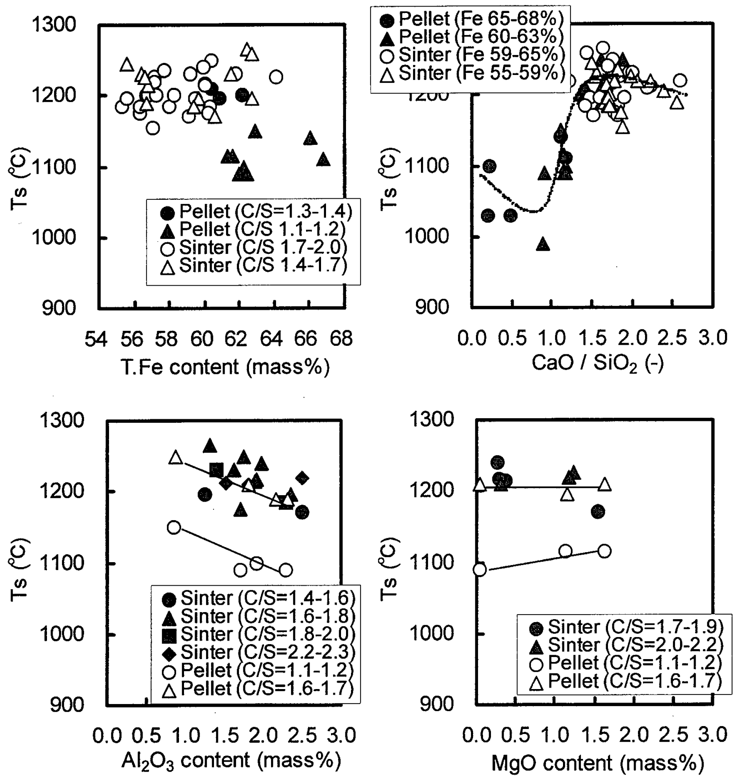

Fig. 2 Influence of chemical composition on softening-melting temperature

liquid phase of the slag falls drastically in this basicity range, because $2CaO{\cdot}SiO_2$ precipitates in a solid phase during the reduction process. The drastic rise of the Td in the high basicity range resulted presumably from the suppression of carburizing due to the above-said precipitation[3]. The reversed influence of Al_2O_3 on the Td in different basicity ranges and the lowering of the Td with an increasing amount of MgO corresponded to the changes in the viscosity and liquid phase amount of slag containing FeO in a low concentration[4]. When the basicity was approximately 0.5, on the other hand, the Td was comparatively high in spite of a sufficiently high ratio of the liquid phase. This was presumably due to the low fluidity[4] and melting-reduction rate[5,6] of the slag.

Fig. 2 shows the relationship between the softening and melting temperature Ts (the temperature at the time when the pressure loss of an ore bed rises to 2.0 kPa) and the composition of the sintered ores and pellets. Since the softening and melting behavior of ore is significantly affected also by its rate of reduction, which is determined by its physical structure, the influences of the ore composition over the Ts were smaller than those over the Td. Nevertheless, the Ts tended to rise as the T.Fe increased, and was lowest in the basicity range from 0.5 to 1.0. Whereas the Ts fell as Al_2O_3 increased, it rose, if slightly, as MgO increased; the basicity caused no difference in these tendencies. These results agreed well with the change of the solidus line temperature of CaO-SiO_2-Al_2O_3-MgO-FeO slag in a high-FeO concentration range[3] and the results of a dripping test simulating the slag[7].

From the above, it became clear that, in order to improve the high-temperature reduction properties of sinter, it was effective to increase the T.Fe, optimize the C/S (1.5 to 2.0) and decrease the Al_2O_3 content.

2.2 Relationship between pore structure and high-temperature reduction behavior of sintered ore

Since an improvement in the reducibility of sinter decreases bulk iron oxide, FeO, it presumably improves the softening and melting behavior of sinter by decreasing the formation of melt during reduction, without having to change the chemical composition of the sinter. **Fig. 3** shows the relationship between the R1000 (the reduction rate at 1,000℃) and pore structure of the same sintered ores and pellets. Roughly speaking, the reducibility tended to improve as the total porosity ratio increased (see Fig. 3 (A)). However, such a tendency did not show clearly; the deviation from such a tendency was large especially in the case of the low-Fe sinter. Seeing this result, it was presumed that the reasons for this were the distribution of pore diameters and the reducibility of the component minerals. The influence of the distribution of pore diameters over the R1000 were studied under the condition of roughly the same total porosity and gangue content, and it was found that the pores 15 μm or less in diameter had a significant influence over reducibility (see Fig. 3 (B)). This indicates that, of ores or pellets having the same chemical composition, those which have a larger volume fraction of pores, especially that of fine pores 15 μm or less in diameter, exhibit significantly improved softening and melting properties. It has to be noted that such an effect had been pointed out also in the relationship between the high-temperature reduction properties and fine pores of commercially produced sinter[8]. In addition, there was a report to the effect that an increase in the volume fraction of fine pores was effective also in improving the strength and low-temperature reduction degradation behavior of sinter and pellets[9].

3. Improvement of Blast Furnace Operation through Improvement of Sinter Quality

3.1 Improvement of blast furnace operation by decreasing SiO_2 and MgO contents in sinter

As seen with Figs. 1 and 2, the studies confirmed the excellent reduction behavior of high-Fe sinter at high temperatures. Aiming at lowering the SiO_2 and MgO contents in sinter and improving its high-temperature reduction properties in order to improve blast furnace operation, as a measure to produce high-FeO sinter, the amount of serpentine, which contains MgO and SiO_2 and had been mixed in the sinter feedstock, was decreased.

First, sintered ores were produced with different mixing rates of serpentine using a test pot, and analyzed their reduction behavior at high temperatures; **Fig. 4** shows the results. The high-temperature

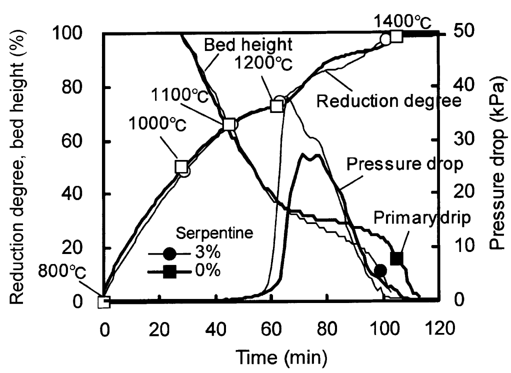

Fig. 4 Improvement of high-temperature reduction behavior of sinter by decreasing serpentine

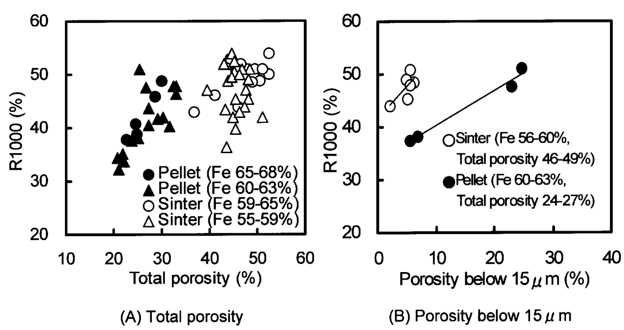

Fig. 3 Dependencies of total porosity (A) and porosity below 15 μ m (B) on R1000

reduction behavior of sinter improved as the mixing rate of serpentine decreased. Although the dripping temperature rose by approximately 15℃ as the MgO amount decreased, its adverse effect was insignificant, but the improvement in the softening and melting properties due to the decrease in the SiO_2 amount was more significant. Then, based on this finding, a series of tests were conducted on Muroran No. 2 Blast Furnace (Case 1 of **Table 1**). At that time, the sintering plant of the Works had mixed 0.7 mass% dunite containing SiO_2 and MgO in the sinter feedstock in place of serpentine. For the purposes of the tests, the mixing of dunite was discontinued to decrease the amounts of SiO_2 and MgO, but the CaO content was kept unchanged, and all the sinter thus produced was fed to No. 2 BF. To avoid the deterioration of the dripping properties of the sinter, the increase in the basicity was controlled to the least possible. In addition, to keep the chemical composition of the blast furnace slag unchanged, lump dunite was charged into the blast furnace from the top.

As a result, the high-temperature reduction properties of sinter improved, the K-value at the lower portion of the blast furnace decreased, and it became possible to increase the pulverized coal injection ratio (PCR) from 140 to 170 kg/t-pig[10]. Thus, after improving the burden distribution, the furnace attained a monthly average PCR of 182 kg/t-pig in December 1998. Since the slag volume of the furnace did not decrease but increased at the tests, the principal reasons of the improvement were presumably the improvement in the reducibility and high-temperature reduction behavior of the sinter. Thereafter, Yawata Works also produced low-SiO_2, low-MgO sinter and used it for No. 4 Blast Furnace of the Works. To avoid the increase in slag volume, the melting point and viscosity of the blast furnace slag were adequately maintained by composition control without top charging of lump flux (Case 2 of Table 1). As a result, the blast furnace attained a productivity coefficient as high as 2.37 t/d/m^3 and a high ore/coke rate of 4.87 with a PCR of 161 kg/t-pig[11].

Table 1 Plant test results of Muroran No. 2 blast furnace and Tobata No. 4 blast furnace

			Case 1		Case 2	
			Muroran 2BF		Tobata 4BF	
Period			'98.1-3	'98.10-12	'98.6-8	'99.2-4
Sinter quality	T.Fe	mass%	58.1	58.4	58.0	58.2
	SiO_2	mass%	5.52	5.10	5.12	4.96
	MgO	mass%	1.20	1.00	1.38	0.86
	Al_2O_3	mass%	1.87	1.89	1.79	1.81
	C/S	–	1.64	1.77	1.76	1.85
	TI/SI	%	73.9	74.6	91.0	91.7
	RDI	%	33.2	40.3	37.6	38.4
	JIS-RI	%	65.9	66.2	63.5	66.5
	S value	kPa • min	814	686	791	585
BF operation	Productivity	t/d/m^3	2.09	2.06	2.30	2.26
	RAR	kg/t-pig	512	508	490	496
	CR	kg/t-pig	373	342	361	336
	PCR	kg/t-pig	139	166	129	160
	Slag volume	kg/t-pig	303	313	284	270
	Al_2O_3 in slag	mass%	15.4	15.8	14.9	15.5
	MgO in slag	mass%	5.5	5.7	6.5	4.0
	C/S in slag	–	1.26	1.26	1.27	1.29

TI: Tumbler index, SI: Shatter index, RDI: Reduction degradation index, S value: accumulative pressure drop, RAR: Reducing agent rate, CR: Coke rate, PCR: Pulverized coal rate

3.2 Improvement of blast furnace operation by decreasing Al_2O_3 content in sinter

Further extending the line of the above tests, in 2001 another series of tests were conducted for decreasing the Al_2O_3 content in sinter under a low-SiO_2 condition at Yawata No. 3 Sintering Machine and No. 4 Blast Furnace (see **Table 2**)[12]. Here, to lower also the FeO content in sinter, the SiO_2 content was decreased by an amount corresponding to the excessive formation of melt due to the decrease in the Al_2O_3 amount, and in addition, decreased also the unit consumption of coke breeze. These measures remarkably improved the reducibility of sinter keeping its strength unchanged; a decrease in the S-value and improvement in the shaft efficiency of

Table 2 Plant test results in Tobata No. 3 sintering machine

		Base	Test
Period		2001.9	2001.10
Pisolite	Ore %	39.1	66.0
SI	%	91.3	91.5
T.Fe	mass%	58.5	59.2
FeO	mass%	6.2	4.6
SiO_2	mass%	5.14	4.72
C/S	–	1.74	1.80
Al_2O_3	mass%	1.76	1.46
MgO	mass%	1.13	1.08
JIS-RI	%	63.7	67.1
S value	kPa • min	1284	1068
η shaft*	%	94.4	97.4

* Results of BIS test

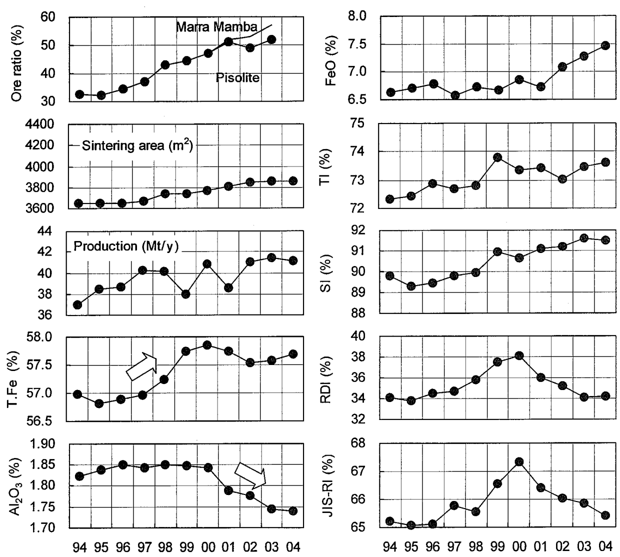

Fig. 5 Changes in quality of sinter product in the past decade

the blast furnace were confirmed through evaluation using a blast furnace inner reaction simulator (BIS). In the actual operation of the blast furnace, efforts were aimed at achieving an improvement in the shaft efficiency by 0.3%, and attained a productivity coefficient of 2.3 t/d/m^3 and a coke rate of 324 kg/t-pig. Thereafter, the new type, low-Al_2O_3 sinter came to be used at all the blast furnaces of Nippon Steel. Now, in spite of increased use of economical iron ores of poor sintering properties, the high-quality sinter is contributing to the high productivity and low consumption of reducing agents of the blast furnaces of the company (see **Fig. 5**).

4. Future Challenges

4.1 Possibility of improving high-temperature reduction behavior of sinter by structure control

Fig. 6 shows the R1200 of ores before assimilation with CaO simulating natural ore remaining in sinter (A) and sinter samples after assimilation with CaO simulating the structure of sinter (B) as a function of the Fe contents of their source ores[1]. In relation to this, **Fig. 7** shows the microstructures of reduced natural ores before assimilation with CaO. The numbers in Fig. 6 are the total porosity and the porosity of pores 15 μ m or less in diameter in percentage before reduction. The Fe concentration and pore structure explain the results of Fig. 6 (A) and (B). The reduction of low-Fe ores delayed markedly near 1,100℃ because of the formation of melt arising from the eutectic point of SiO_2-Al_2O_3-FeO slag. The reason why Ore B exhibited a low reduction rate in spite of a low content of gangue is presumably that the porosity rate was low and the size of the ore grains was large.

On the other hand, whereas some low-Fe ores exhibited low reduction rates before the assimilation with CaO, their reducibility after assimilation was high. This indicates that it is possible to improve the high-temperature reduction properties of sinter by changing its mineralogical and pore structures by controlling the melting during the sintering process, without having to change the chemical composition. In addition, the types of bonding phase were different from ore brand to ore brand. However, the influence of the different types of bonding phase over their softening and melting behavior is unclear at present. To cope with the increasing deterioration of iron ore resources, fundamental examination into further depths of this aspect is required. Furthermore, while increasing the volume fraction of fine pores is effective in improving the high-temperature reduction behavior of sinter, many aspects of the formation process of fine pores and the sintering conditions for forming them are still unclear, and further studies are required[13].

4.2 Index of high-temperature reduction behavior of sinter for blast furnace operation

Conventionally, the reduced index (RI) has been used as the indicator of the degree of reduction of sinter in blast furnace operation

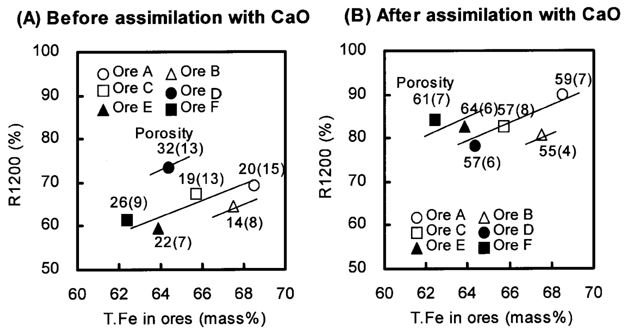

Fig. 6 Results of R1200 of natural ore samples (A) and of sintered sample (B) as a function of Fe content in source ores after dehydration

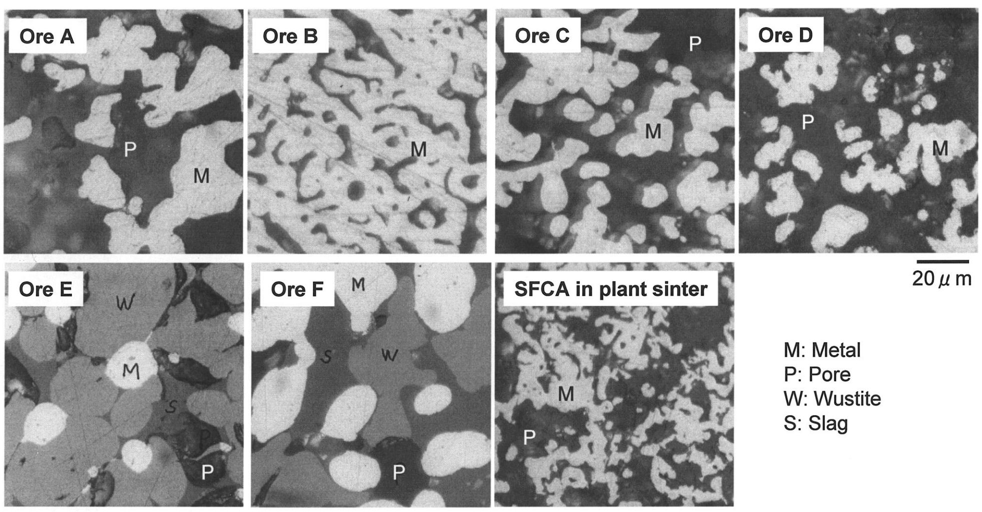

Fig. 7 Microstructures of natural ores after reduction (magnification × 500)

under the Japanese Industrial Standard. However, since the RI is an indicator based on a simple method of reduction evaluation, it is not always suitable for expressing improvements in blast furnace operation by use of low-slag sinter[14]. Therefore, a new indicator capable of correctly expressing the degree of reduction of sinter in actual blast furnace operation is required.

5. Summary

In the pursuit of enhancement of the reducibility and high-temperature reduction properties of sinter to improve blast furnace operation, the following findings and results were obtained:

(1) The high-temperature reduction properties of sinter depend on its chemical composition and pore structure. The liquid phase amount (or, indirectly, liquidus line temperature), viscosity and melting and reduction rate of slag coexisting with hot metal and containing FeO in a low concentration had influence over the carburization behavior of the hot metal, and this determines the dripping properties of the metal. On the other hand, the softening and melting behavior of sinter depends on its chemical composition, pore structure and mineralogical structure. The softening and melting temperature of sinter changes depending on the liquid phase amount (or, indirectly, liquidus line temperature) at low temperatures and reducibility of slag containing FeO in a high concentration.

(2) An increase in the Fe content of sinter, optimization of its C/S ratio (1.5 to 2.0) and a decrease in the Al_2O_3 content are effective in improving the high-temperature reducibility of sinter. In addition, increasing the volume fraction of fine pores 15 μm or less in diameter is also effective.

(3) Based on the above findings, a new type of sinter having low contents of SiO_2, MgO and Al_2O_3 excellent in high-temperature reduction properties has been developed and used at all the blast furnaces of Nippon Steel. The new type of sinter has contributed to the improvement of blast furnace operation through enhancement of indicators such as the reducing agent ratio.

(4) For further improvement, it is necessary to clarify the influence of the structure of sinter over its high-temperature reduction properties and establish methods for controlling the mineralogical and pore structures of sinter. It is also necessary to review the conventional reduction index and introduce a new one more suitable for delicate control of blast furnace operation.

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