Sintering Technology Using Parallel Granulation Process at High Pellet Feed Ratio

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Kakogawa Works of Kobe Steel, Ltd. has a set of sinter and pellet plants for the production of blast furnace raw materials. Recently, the use of magnetite fine ore has attracted attention while deterioration of iron ore grade. We clarified the problem of granulation and firing in using large quantity of magnetite fine ore, and developed countermeasures.

The most serious problem is forming un-granulated fine and huge agglomerates which causes decrease of permeability and deterioration of productivity. Since the strength of huge agglomerates is low, they collapse during transportation and sintering process. And then, they decrease permeability of packed bed and reduce productivity.

Selective granulation of magnetite fine ore is effective to suppress un-granulated fine and huge agglomerate. We propose the parallel granulating process which produce the double layer mini-pellet of magnetite fine ore which consists of core and adhesive layer. Double layered structure prevents collapse effectively because of aggregate effect of core particle. In addition, as the adhering layer of magnetite fine ore become thinner, magnetite is fully oxidized. Using double layer mini-pellet improves productivity and reduces coke consumption.

KEY WORDS: sintering; granulation; magnetite fine ore; pellet feed; mini-pellet; permeability; oxidization.

1. Introduction

The main raw material of blast furnace is sinter, even in the Kakogawa Works which has a set of sinter and pellet plants, the blending ratio of sinter in blast furnace raw materials accounts for 40 to 50 mass%. Sinter plant use mainly iron ore with a particle less than about 5 mm, which called sinter feed. High grade sinter feed produced in Australia and Brazil has been used at steelworks in Japan. In recent years, high-grade iron ore is depleted. Al2O3 content of iron ore has risen, and it makes strength and RDI (Reduction Degradation Index) of sinter worse. Additionally it increases slag ratio in blast furnace, which makes the performance of blast furnace worse. Therefore, brand new high-grade iron ore is necessary to sintering process.

Some of high-grade iron ores called pellet feed, finer than sinter feed, has been used in pelletizing process. Especially, pellet feed of magnetite is expected to use in sintering process.1) Magnetite pellet feed is very fine, and includes 20–30% of Fe(II). It is well known that the use of large amount of fine ore makes the size of agglomerate increase in granulating process. Under fine ore ratio higher than 30 mass% huge agglomerates of over 8 mm increase too much.2) As the strength of huge agglomerates are low, they collapse in the transporting process from the drum mixer to the sintering machine and reduced the permeability in packed bed.

On the other hand, heat generation by Fe(II) oxidation is expected to reduce coke consumption. Paradoxically, sufficient oxidation of magnetite is important factor for production of proper quality sinter.3,4) It has been reported that oxidation of Fe(II) is inhibited in where oxygen is low by combustion of coke.5) Coexistence with limestone which is a source of calcium-ferrite melt also inhibits oxidation of Fe(II) via block of oxygen diffusion.6) In response to these results, Matsumura et al. proposed the selective granulation process in which magnetite pellet feed is granulated separately from limestone and coke for promoting the oxidation.6) It has decreased the residual Fe(II), and improved reducibility and strength of product sinter.

For industrial use of large amount magnetite fine ore, it is necessary to design optimum granulation process that improves both of permeability and oxidization. Therefore, we propose the parallel granulating process which produces the double layer mini-pellet of magnetite fine ore and conventional agglomerate. In this report, we show the property of the double layer magnetite mini-pellet, improvement of productivity and reduction of coke consumption by the parallel granulating process.
2. Experiment

2.1. Raw Materials and Granulation Test [Test 1]

The particle size distribution and chemical composition of the iron ore used in the experiment are shown in Fig. 1 and Table 1. Ore A and B are hematite sinter feed. Ore M1 and M2 are magnetite pellet feed. Table 2 shows the blending conditions of raw materials for the granulation test. Lime- stone and silica sand were added to adjust the CaO/SiO$_2$ of the sintered ore into 2.1 at 5.4 mass% SiO$_2$. Granulation of conventional agglomerates was executed with a drum mixer (diameter 820 mm, length 800 mm). Granulation time was 2 minutes, the rotating rate was 13 rpm, and the sample weight was 65 kg. Then moisture of 6.2 to 7.7 mass% was added in advance. Size distribution (−1 mm, +1 mm, +3 mm, +5 mm, +10 mm) of agglomerates was measured immediately after granulation.

![Particle size distribution of iron ores.](image)

**Table 1.** Chemical composition of iron ores (mass%).

<table>
<thead>
<tr>
<th></th>
<th>T.Fe</th>
<th>FeO</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>Al$_2$O$_3$</th>
<th>C.W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>66.00</td>
<td>0.05</td>
<td>1.40</td>
<td>0.01</td>
<td>1.30</td>
<td>1.25</td>
</tr>
<tr>
<td>Ore B</td>
<td>58.60</td>
<td>0.05</td>
<td>4.60</td>
<td>0.07</td>
<td>1.54</td>
<td>9.05</td>
</tr>
<tr>
<td>Ore M1</td>
<td>68.90</td>
<td>28.30</td>
<td>2.04</td>
<td>0.39</td>
<td>0.64</td>
<td>–</td>
</tr>
<tr>
<td>Ore M2</td>
<td>67.50</td>
<td>28.20</td>
<td>5.22</td>
<td>0.16</td>
<td>0.15</td>
<td>–</td>
</tr>
</tbody>
</table>

Permeability was evaluated with acryl cylinder (diameter 130 mm) in which agglomerates were packed. Permeability index defined as J.P.U (Japanese Permeability Unit) was calculated by Eq. (1) based on the measurement of pressure loss of packed bed. Air flow rate supplied from the bottom was 300 L/min, and height of packed bed was 100 mm.

$$J.P.U. = \frac{Q}{A(h/\Delta P)^{0.6}} \quad (1)$$

$Q$: air flow rate (m$^3$/min), $A$: cross sectional area of cylinder (m$^2$), $h$: height of packed bed (mm), $\Delta P$: pressure loss (mmAq)

2.2. Evaluation of Property of Mini-pellet [Test 2, 3]

Tire type pelletizer (diameter 450 mm, rotating rate 30 rpm) was used to granulate mini-pellet of magnetite fine ore. The size of mini-pellets were adopted 3 to 5 mm equal to the average of conventional agglomerates. Double layer mini-pellets were prepared as follows. At first, core materials were charged. Second, magnetite fine ore and binder were added (core/magnetite fine = 20/80 mass%). Then the total moisture was gradually added up to 6.9 mass%. Core materials for double layer mini-pellets were selected as return fine sinter and hematite ore (ore A), size of which was adopted 1 to 3 mm. Core particles were immersed in water overnight and wiped off surface water before use. The moisture after immersion was 1.3 mass% for sinter and 4.5 mass% for Ore A. Quick lime less than 1 mm or slaked lime less than 0.1 mm was used as a binder (binder ratio to magnetite fine was 0.2 to 2.0 mass%).

The strength of the Ore M1 mini-pellets was evaluated using I-shaped tumbler test apparatus (diameter 110 mm, length 500 mm) [Test 2]. Tumbling time was 2 minutes in 20 rpm. After tumbling the residual ratio of over 3 mm was defined as the strength of mini-pellets.

The oxidation rate of simple Ore M1 mini-pellet without core was measured at 800 to 1 200℃ with a vertical electric tube furnace (diameter 70 mm) [Test 3]. After heating in nitrogen atmosphere up to the fixed temperature, gas flow was switched from nitrogen to air for a predetermined time, and cooled in nitrogen atmosphere again. Gas flow rate was 5 Nl/min. The oxidation degree was calculated by chemical analysis. Then the oxidation rate is set to 0% at the initial state of Ore M1 and 100% at complete hematite conversion.

2.3. Pot Test [Test 4, 5]

Blending conditions of raw materials for the pot test are shown in Table 3. Scheme of pot tests are shown in Fig. 2. A small round pot (diameter 130 mm × height 400 mm) [Test 4] and a large square pot (280 mm × 280 mm × height 590 mm) [Test 5] were used. Mini-pellets for small pot test were granulated by the method described in the previous section. At large pot test, double layer mini-pellets were granulated by drum mixer. Sinter containing −1 mm fine, Ore M2 and slaked lime were simultaneously charged in drum mixer, and moisture was gradually added up to 6.9 mass% (ratio core to fine is almost same with mini-pellets for small pot test). The other materials were granulated by a conventional method. Mini-pellet (granulation line 2) and conventional agglomerates (granulation line 1) were mixed by agitate mixer for 1 minute and used for the pot test (Fig. 2). Homogeneous bed condition without segregation is
applied in a small pot, and segregated bed condition equal to the actual plant with the charging equipment simulator with drum feeder and sloping chute (width 0.4 m, length 1.1 m, angle 59 degree, height of end point 1.2 m), pallet car (height 590 mm, length 2 m) is applied in a large pot. The packed bed was divided into 12 parts in the height, and the agglomerate size distribution (−1 mm, +1 mm, +3 mm, +5 mm, +10 mm) and the chemical composition of each part were analyzed.

The suction pressure was kept constant, −1000 mmAq for a small pot and −1600 mmAq for a large pot. After sintering, sinter cake was dropped from 2 m height (2 times for
small pot, 4 times for large pot), and sinter of over 10 mm was collected as a product. Products of 10 to 50 mm was dropped 4 times further from 2 m height, and the residual ratio of over 10 mm was defined as shutter strength.

2.4. Diffusion Couple Test Simulating Mini-pellet Interface [Test 6]

The melt assimilation property of ore is an important factor affecting quality. Okazaki evaluated the penetration of melt in a diffusion couple test in which two types of tablets were stacked.\(^7\) Mill scale containing Fe(II), which has properties similar to magnetite, melts excessively in firing process.\(^8\) In this report, simulating the reaction at the mini-pellet interface, diffusion couple test was executed with tablets (diameter 10 mm, height 10 mm) at 1 200 to 1 300°C under nitrogen atmosphere. The sample was put on a platinum basket, placed in an electric furnace over 1 minute, and held for 2 minutes. After heating, samples were cooled in air.

Tablets A: diffusion couple of high CaO mixture and magnetite, simulating outer surface of mini-pellet.

Tablets B: diffusion couple of fine sinter and magnetite, simulating surface of core in mini-pellet.

The composition of the high CaO mixture was set equal to that of adhesion layer of the case of granulation line 1 (Table 3). After cooling, structure of cross section of tablets were observed with a microscope.

2.5. Actual Plant Test [Test 7]

The equipment flow of sintering machine at Kakogawa works is shown in Fig. 3. There are two parallel drum mixers. Double layer mini-pellets were produced at granulation line 2 using Ore M2 and fine sinter, burned lime.

3. Experimental Results and Discussion

3.1. Effect of Magnetite Pellet Feed on Granulation

Figure 4 shows the change in the size distribution of the agglomerates against to increase of magnetite fine ore ratio at 7.2 mass% water content for granulation [Test 1]. Un-granulated fine less than 1 mm and huge agglomerate over 10 mm increased. Un-granulated fine greatly increased up to 10 mass% of magnetite fine ore ratio, and then gently decreased. Huge agglomerate increased monotonically. Constituents of the un-granulated fines and huge agglomerates specified by chemical analysis are shown in Fig. 5. Increase of the un-granulated fine is due to a fine part of hematite sinter feed at a low ratio of magnetite fine ore. Magnetite fine ore in un-granulated fine gradually increased. Most of the huge agglomerates were composed of magnetite fine ore. Therefore, it is presumed that magnetite fine ore with adhesion is granulated preferentially, and the other fine materials, limestone, coke and fine of hematite ore, are left as un-granulated fine. On the other hand, it is presumed that large amount of magnetite fine ore forms huge agglomerates with thick adhering layer due to decrease of core particles.

The influence of magnetite fine ore on permeability is
shown in Fig. 6. Permeability remarkably decreased by un-granulated fine at first, and then decreased by huge agglomerates. Therefore, optimum granulation control, suppressing huge agglomerate and un-granulated fine, is important to improve the permeability.

Generally, increase of water content for granulation is effective to reduce un-granulated fine. In order to reduce un-granulated fine as same as the reference level at 30 mass% of magnetite fine ore, increase of about 0.5 mass% water content is necessary as shown Fig. 7(a). But, forming huge agglomerate was emphasized under high water content (Fig. 7(b)). These show the difficulty of granulation control by water content adjustment.

### 3.2. Structural Design of Double Layer Mini-pellet

In sintering process, weak agglomerates collapse to fines during transporting and charging process. Countermeasure to improve the strength of mini-pellet are shown below.

1. Addition of core to agglomerate: Double layered structure with core prevent collapse effectively.
2. Addition of binder: Binder in adhering layer suppresses peeling off of magnetite fine ore.

The strength of the double layer mini-pellet without binder is shown in Fig. 8 [Test 2]. Comparing to simple mini-pellet without core, strength was improved. Core of return fine of sintered ore improved strength more than core of hematite ore. A saturated moisture content of hematite ore (ore A) was more than sintered ore. So, more water works to stick magnetite pellet feed in use of sintered ore as core. As the penetration of water into fine pores progresses over several hours,9) sintered ore with low hygroscopicity is advantageous in terms of effective granulation water.

The effect of binder on mini-pellet without core is shown in Fig. 9 [Test 2]. Both quicklime and slaked lime greatly improved strength up to 0.5 mass%, since ultra-fine particles crosslinked contacts and strengthened bonding in mini-pellet.10) The effect of slacked lime is greater than quicklime because it includes more ultra-fine particles. Slaked lime
without hydration reaction is suitable for stability of granulation water amount.

It has been reported that magnetite tend to aggregate and huge aggregates do not be well sintered.\textsuperscript{11) As shown in Fig. 10, an un-oxidized magnetite core remained in the sintered cake of the pot test using the simple mini-pellet without core [Test 4]. As it takes several minutes for complete oxidation even in high temperature over 1 000°C (Fig. 11) [Test 3], a thin adhesive layer is better. Therefore, a double layered structure with core which reduces the thickness of adhesive layer is preferable to promote the oxidation of magnetite.

3.3. Effect of Double Layer Mini-pellet on Productivity Improvement

The results of the small pot test are shown in Fig. 12 [Test 4]. Productivity was greatly reduced under the simple mixing condition of magnetite fine ore (case a). Although it was recovered by using the simple mini-pellet without core (case b), it did not reach the reference level of 0 mass% of magnetite fine ore. Addition of binder to simple mini-pellet without core isn’t valid in productivity (case c). Changing into the double layered structure by adding core particle improved further (case d). Binder was very effective to the double layer mini-pellet (case e).

Improvement of the productivity using double layer mini-pellets with binder is estimated as follows; (1) Peeling in the drying zone is suppressed by crosslink of ultra-fine slaked lime. (2) Crushing in the wet zone was suppressed by aggregate effect of core. Residual mini-pellets like Fig. 10 weren’t recognized in sintered cake of the pot test using double layer mini-pellet with core.

Results of diffusion couple test is shown in Fig. 13 [Test 6]. Assimilation wasn’t observed at the interface of tablets A (surface of mini-pellet) at 1 200°C. Tablets B (internal of mini-pellet) assimilation was observed at interface around sinter (core). Because sinter includes calcium ferrite of low melting point, it is presumed that the assimilation started from low temperature. High CaO material and sinter began to melt from 1 250°C, completely melted at 1 300°C, and assimilated with magnetite fine ore. The double layer mini-pellet with core of sinter has advantage that assimilation progresses from both of inside and outside.
3.4. Effect of Double Layer Mini-pellet on Coke Consumption Reduction

Using a charging equipment simulator modifying collapse and segregation equivalent to the actual sintering machine, we conducted an integrated evaluation of the parallel granulating process. Figure 14 [Test 5] shows the profile of average agglomerate size and the FeO content along height of packed bed. The segregation from the bottom to 400 mm was low in the case of mini-pellet, and size distribution was almost equal to the base condition. Local concentration of mini-pellet wasn’t observed either from the distribution of the FeO content.

Next, the results of the large pot test are shown in Fig. 15 [Test 5]. Productivity was improved like as small pot test. The strength of product was higher than the base condition at case 1 (3.8 mass% coke ratio), but lower at case 2 (3.4 mass% coke ratio). 0.4 mass% of coke ratio corresponds to equivalent to oxidation heat of magnetite fine ore in agglomerate, when all magnetite are oxidized to hematite. So, heat generation of case 1 (3.8 mass% coke ratio and 30 mass% of magnetite fine ore) is same as that of reference.
(4.2 mass% of coke ratio and 0 mass% of magnetite fine ore). Difference in FeO analysis wasn’t found in each sinter cake, so that magnetite was sufficiently oxidized. It was presumed that decrease of adhering fine layer of magnetite pellet feed by adding the core particle worked favorably on oxidation of magnetite.

The maximum temperature and the holding time at over 1 000°C during firing are shown in Fig. 16. The profile of maximum temperature under the condition of 3.8 mass% coke was almost same as the base condition and the holding time was longer. Under the condition of 3.4 mass% coke, the maximum temperature was lower and the holding time much shorter than the base condition.

It is assumed that the factor of improvement in strength and productivity under the same heat input condition is due to the difference in heat transfer mechanism between magnetite oxidation and coke combustion. Oxidation of magnetite in which the solid itself generates heat is more superior in heat efficiency than coke combustion in which heat mainly transfers from gas to solid by convection. The double layer mini-pellets is expected to reduce the coke consumption more than equivalent of oxidation heat of magnetite under the constant shutter index of product sinter.

3.5. Effect Verification by Actual Plant Test

Figure 17 shows the transition of the operation during

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**Fig. 15.** Productivity improvement using magnetite mini-pellet at sinter simulator [Test 5].

**Fig. 16.** Change of heat pattern in direction of bed height [Test 5]. (a): maximum temperature, (b): holding time at over 1 000°C. (Online version in color.)

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<table>
<thead>
<tr>
<th>Granulation method</th>
<th>Single (BASE)</th>
<th>Parallel (Double layer mini-pellet)</th>
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<tbody>
<tr>
<td>Coke breeze ratio</td>
<td>4.2%</td>
<td>3.8%</td>
</tr>
<tr>
<td>Ore M2 ratio</td>
<td>0%</td>
<td>30%</td>
</tr>
<tr>
<td>Core type</td>
<td>-</td>
<td>sinter</td>
</tr>
<tr>
<td>Staked time</td>
<td>-</td>
<td>0.5%</td>
</tr>
<tr>
<td>Shutter index (%)</td>
<td>87</td>
<td>84.5</td>
</tr>
</tbody>
</table>
the period using the double layer mini-pellets in Kakogawa sintering plant [Test 7]. Although the productivity decreases temporarily in the process of increasing the magnetite pellet feed, recovered by using the double layer mini-pellet despite the high magnetite pellet feed blending rate. As the change in the product FeO was small, it was considered that the magnetite pellet feed was also sufficiently oxidized. The reduction of the coke equivalent to oxidation heat of magnetite could be verified. Further reduction of coke can be expected as strength of sinter product was improved.

4. Conclusion

We have gotten the following knowledge by achievement of granulation and pot test, and verified that the parallel granulation process is effective in order to realize large quantity use of magnetite fine ore.

(1) A double layer mini-pellet by selectively granulating magnetite fine ore increases productivity, which is caused by permeability improvement. Improvement of permeability is due to the suppression of peeling by slaked lime and the reduction of collapse by aggregate effect of core particle.

(2) Double layer mini-pellets were also superior than no-core mini-pellets in terms of oxidation and assimilation.

Under sufficient assimilation and oxidation of magnetite, it is expected to reduce the coke consumption which is more than equivalent of oxidation heat of magnetite.

(3) The effect of double layer mini-pellet was verified by plant test with two-line parallel granulation facilities in Kakogawa works.

REFERENCES