Improvement of Sinter Productivity by Control of Magnetite Ore Segregation in Sintering Bed

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Recently, the quality of sinter feed ore used in sintering process has deteriorated. In particular, T.Fe has decreased and gangue component has increased in the sinter feed ore. Increase of gangue is not only the factor to influence sinter qualities, but also the factor to increase coke ratio in the blast furnace operation as the increase of slag ratio. Therefore, to cope with the deterioration of iron ore qualities, studies on alternative iron ore resources and development of its utilization technology have been required.

In that kind of new iron ore resources, authors focus on high grade magnetite fine. In the past, there are some studies about the effect of mixing ratio and size of magnetite fine on productivity and quality, but there are few studies about magnetite fine segregation in charging. In addition, magnetite fine decreases sinter productivity by the decrease of permeability of sintering bed. A new study for using large amount of magnetite fine is required.

In this research, the control method of magnetite fine segregation by magnetic force at charging and the improvement of sinter productivity by this method was studied. The effect of upper segregation of magnetite fine was studied through the analysis of melting behavior and interfacial reaction of calcium ferrite melts into hematite substrate and magnetite substrate.

KEY WORDS: sinter; magnetite; melting; interfacial reaction; segregation; magnetic force.

1. Introduction

Recently, the quality of sinter feed ore used in sintering process has deteriorated. In particular, T.Fe has decreased and gangue component, e.g. SiO₂ and Al₂O₃ has increased in the sinter feed ore. It was reported that the reducibility of CaO·FeO·SiO₂ is lower than 2CaO·Fe₂O₃, CaO·Fe₂O₃ and CaO·2Fe₂O₃ in the mineral texture of self-fluxing sintered ore.¹ Moreover, increase of Al₂O₃ in iron ore decreases fluidity of melts generated during sintering reaction and disturbs the bonding between particles and rearrangement of pores, as a results sinter strength decreases.²

Therefore, to cope with the deterioration of iron ore qualities, usage of high grade iron fine instead of low grade iron ore is studied. But, fine ore usage for sintering process decreases sinter productivity by decreasing permeability in the sintering bed. Sakamoto et al. predicted particle size reduction of iron ore in the future and offered the new process characterized by disk pelletizer (HPS: Hybrid Pelletized Sinter process).³ There are urgent issue to enhance the readiness of iron resources like studying on alternative iron ore resources and development of its utilization technology.

In these days, magnetite fine ore have been focused on such a new iron ore brand. Ikeno et al. studied about the effects of magnetite fine particle size on the sintering process, and formulate the relationship between the blending ratios by different particle size and sintering productivity and quality.⁴ Moreover, Ando et al. reported that magnetite is the essential material for the sintering reaction and offered optimum size distribution of magnetite fine ore.⁵ But there are few studies about the effect of magnetite fine ore segregation in the sintering bed. Moreover, it is concerned that magnetite fine ore decrease sintering productivity, a new study for using large amount of magnetite fine is required.

Authors studied about production improvement by the control effect of magnetite fine ore segregation. It is well known that sintered ore in the upper zone has lower strength compared with lower zone.⁶ This research intended to improve the sinter strength by upper segregation of magnetite fine ore. At first, the difference of melting and interface reaction of Calcium-ferrite (Ca-ferrite) with hematite and magnetite is studied. Moreover, control method of magnetite fine ore segregation was studied using magnetic braking feeder,⁷ and its influence to sinter productivity was evaluated.
2. Experimental Method

2.1. Effect of Fe$_2$O$_3$ and Fe$_3$O$_4$ Substrate on Ca-ferrite Melting Behavior

In the sintering reaction, Ca-ferrite melt consisting primary Fe$_2$O$_3$ and CaO was generated. Ca-ferrite acts as the binder to bond ores. And it is the factor to express the sinter strength. Therefore, penetrating behavior of Ca-ferrite melt and reaction behavior between melt and ore are the important characteristics. In this research, Fe$_2$O$_3$ and Fe$_3$O$_4$ substrates were prepared and their interfacial physical property to Ca-ferrite melts were evaluated.

2.1.1. Method of Making Fe$_2$O$_3$ and Fe$_3$O$_4$ Substrate

Fe$_2$O$_3$ reagent (99.9%, mean size: 0.5 \(\mu\)m) and Fe$_3$O$_4$ (99.0%, mean size: 0.5 \(\mu\)m) reagent were used to make substrates. Two type of substrates, dense and porous, were made by controlling of molding pressure. At first, slurry was made by ball milling for 24 h. Polyethylene pot (500 ml) and ZrO$_2$ balls were used for ball milling. Reagent and balls were charged in the pot. And the weight ratio was 1/1. After that ethanol was poured into the pot until reagents and balls were soaked (Fe$_2$O$_3$ for 200 g, Fe$_3$O$_4$ for 120 g). Flour was also added by 1 wt% for only making porous substrates. After the ball milling, ethanol was dried and samples were regulated by the screen (335/367 \(\mu\)m). After that, its samples were casted by 30 mm mold. Cold isostatic pressing was carried out for dense substrate and its molding pressure was set at 30 MPa. Uniaxial pressing was used for porous one and its molding pressure was set at 3 MPa.

Resultant moldings were sintered in the following method. Fe$_2$O$_3$ was sintered in the air but then Fe$_3$O$_4$ was sintered in the 7%CO-93%CO$_2$ atmosphere for preventing oxidation of Fe$_2$O$_3$. For dense Fe$_2$O$_3$ substrate, their sintering temperature was rose to 1300°C by 10°C/min and kept for 3 hr. For dense Fe$_3$O$_4$ substrate, their sintering temperature was rose to 1350°C by 10°C/min and kept for 3 hr. For porous Fe$_2$O$_3$ and Fe$_3$O$_4$ substrate, they were kept at 150°C for 0.5 h to volatize flour at first and their sintering temperature was rose to 900°C by 5°C/min and kept for 10 min. After sintering, all samples were cooled by 10°C/min. After pulse polish with diamond slurry (1 \(\mu\)m), they were washed by soapy water, ultrapure water, propanol, and acetone in this order. After that, relative density of every substrate was measured by the Archimedes method. Figure 1 shows the SEM image, relative density and porosity of every substrate.

Next, Ca-ferrite tablet was made from Fe$_2$O$_3$ (99.9%, mean size: 0.5 \(\mu\)m) and CaCO$_3$ regents. Both regents were mixed in order that mole ratio of Fe$_2$O$_3$ and CaO is 1/1 by the alumina mortar. Mixing sample was measured off by 30 g and melted at 1600°C for 30 min in Pt crucible. After that, it was chilled on copper plate. After milling of Ca-ferrite sample, Ca-ferrite sample was measured off by 0.2 g or 0.5 g, and its tablet was made by 7 mm mold with 156 MPa.

2.1.2. Experimental Apparatus and Method

Horizontal electric furnace was used in this experiment. Each iron oxide substrate was set on the heat-resistant bricks, and Ca-ferrite tablet (0.2 g) was set on the iron oxide substrate. The temperature was increased to 1300°C by 10°C/min and kept for 0 min, 3 min and 10 min in the air for Fe$_2$O$_3$ or 7%CO-93%CO$_2$ atmosphere for Fe$_3$O$_4$. After keeping, the furnace was turned off and samples were cooled to room temperature. Next, these samples were drawn from the furnace and mounted by resins. After cutting, they were polished and washed as shown in section 2.1.1. Then, EPMA (accelerating voltage: 20 kV) mapping

<table>
<thead>
<tr>
<th></th>
<th>Dense</th>
<th>Porous</th>
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<tbody>
<tr>
<td>Fe$_2$O$_3$</td>
<td>SEM image</td>
<td>50(\mu)m</td>
</tr>
<tr>
<td>Relative ρ (%)</td>
<td>97.8</td>
<td>51.7</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>2.2</td>
<td>48.3</td>
</tr>
<tr>
<td>Fe$_3$O$_4$</td>
<td>SEM image</td>
<td></td>
</tr>
<tr>
<td>Relative ρ (%)</td>
<td>94.3</td>
<td>67.8</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>5.7</td>
<td>32.2</td>
</tr>
</tbody>
</table>

Fig. 1. Physical properties of sintered tablets.
was carried out at one area near the interface for 0 min sample, at three areas near interface, middle part of inter-
fusion area and bottom part of interfusion area for 3 min and 10 min samples. And penetration distance was also 
measured by EPMA mapping data.
Wettability of Ca-ferrite melt to each iron oxide substrate
during temperature rising was also evaluated in the same 
experiment. In this experiment, the apparent contact angle of 
Ca-ferrite tablet (0.5 g) was measured three times by using 
the graphics software.

2.2. Study about Upper Segregation of Magnetite Fine 
Ore
Magnetic braking feeder is the charging device to make 
the magnetic force to the materials having high magnetic 
susceptibility out of sinter raw materials flowing on the 
chute by permanent magnet placed at the back side of the 
chute. The materials applied the magnetic force decrease 
their dropping velocity and were charged in the upper zone 
of sintering bed. Then, the effect of magnetic field formed 
by the magnetic braking feeder on the segregation behavior 
of magnetite fine ore having high magnetic susceptibility by 
discrete element method (DEM) models.

2.2.1. Outline of the DEM Model
PFC3D was used in this calculation. In this calculation, 
four type of particles (A–D) were defined and magnetic 
force was applied to only particle D on the chute. Table 1 
shows the physical parameter of each particle and its mix-
ing ratio.

Figure 2 shows calculation field. At first, the pallet 
(500 mmH×200 mmW×5 000 mmM) was defined and the 
inclined plate was set in the pallet at the angle 50° which is 
slightly greater than repose angle of particles for decrease 
of calculation load. 20 mm particles were also set and fixed

Table 1. Parameter and mixing ratio of particles in DEM simu-
lation model.

<table>
<thead>
<tr>
<th>Particles</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>30.0</td>
<td>20.0</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.5</td>
<td>2.4</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Mixing ratio (%)</td>
<td>2.0</td>
<td>20.0</td>
<td>68.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

at the bottom of the pallet not to roll the particles. This 
pallet moved at 4.35 m/min. The chute was set at 110 mm 
above the top of the pallet at the angle 51° and its length 
is 1 000 mm. The particles were charged from top of the 
chute at 10 kg/s based on Table 1. The viscosity coefficient 
of particles were set at 0.5×10⁶ N/m in both normal direc-
tion and tangential direction and to viscosity coefficient of 
wall is set at 2.0×10⁶ N/m in normal direction and set at 
2.0×10³ N/m in tangential direction to meet repose angle 
of particles in the calculation to that of actual sinter raw 
materials. The friction coefficient was set at 0.65 in both 
particles and walls condition.

2.2.2. Calculation Condition of DEM Model
Figure 3 shows the application condition of the magnetic 
force on the chute. Magnetic force was applied within the 
area 500 mm from the bottom of the 1 000 mm chute. In the 
Case 1, the magnetic force was not applied. The magnetic 
forces was set at 0.005 N, 0.05 N and 0.5 N in each condi-
tion, Case 2, Case 3 and Case 4.

2.3. Charging Test with Charging Simulator

2.3.1. Outline of Charging Simulator
The charging test of magnetite fine ore with magnetic 
braking system was carried out by the charging simulator 
to confirm the calculation results of DEM model.7) The 
size of this simulator was fit to Kurashiki No. 3 sintering 
machine in height direction, and contracted into 400 mm in 
width direction. Its chute angle was set at 51° as with DEM 
model. Permanent magnet plate was placed at the back side 
of the chute, and the magnetic flux density was controlled 
by the adjustment of distance between chute and magnet. 
Pallet sized 500 mmH×400 mmM was moved at 3.0 m/
min. Sintered ores were bedded in 20 mm as the hearth 
layer. Moreover, this pallet has the removal part and it was 
used to pot tests as the cubic pot sized 500 mmH×400 
mm×400 mm.

2.3.2. Experimental Condition
Table 2 shows blending condition of the charging test. 
South American hematite ore and Australian pisolite ore 
were used as base raw materials. South American magneti-
tite fine ore containing 29.5 mass%-FeO was blended in 
20 mass% of the all materials. Table 3 shows chemical

Table 2. Blending condition of the charging test.

<table>
<thead>
<tr>
<th>South American hematite ore</th>
<th>Australian pisolite ore</th>
<th>South American magnetite fine ore containing 29.5 mass%-FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>50%</td>
<td>10%</td>
</tr>
</tbody>
</table>

The size of this simulator was fit to Kurashiki No. 3 sintering 
machine in height direction, and contracted into 400 mm in 
width direction. Its chute angle was set at 51° as with DEM 
model. Permanent magnet plate was placed at the back side 
of the chute, and the magnetic flux density was controlled 
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Table 3. Chemical properties.

<table>
<thead>
<tr>
<th>South American hematite ore</th>
<th>Australian pisolite ore</th>
<th>South American magnetite fine ore containing 29.5 mass%-FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>FeO</td>
<td>FeO</td>
</tr>
<tr>
<td>30%</td>
<td>30%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Fig. 2. Calculation field of DEM simulation model.

Fig. 3. Calculation condition of applied magnetic field on chute.
Table 2. Blending ratio for charging test.

<table>
<thead>
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<th>(mass%)</th>
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<tbody>
<tr>
<td>Hematite ore</td>
<td>25.0</td>
</tr>
<tr>
<td>Pisolite ore</td>
<td>21.2</td>
</tr>
<tr>
<td>Magnetite fine</td>
<td>20.0</td>
</tr>
<tr>
<td>Silica sand</td>
<td>0.8</td>
</tr>
<tr>
<td>Return fine</td>
<td>20.0</td>
</tr>
<tr>
<td>Limestone</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Table 3. Chemical composition and under 125 μm ratio of ores.

<table>
<thead>
<tr>
<th></th>
<th>T,Fe</th>
<th>FeO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>−125 μm</th>
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<tbody>
<tr>
<td>Hematite ore</td>
<td>64.3</td>
<td>0.1</td>
<td>2.8</td>
<td>1.9</td>
<td>19.0</td>
</tr>
<tr>
<td>Pisolite ore</td>
<td>57.3</td>
<td>0.1</td>
<td>5.9</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Magnetite fine</td>
<td>69.4</td>
<td>29.5</td>
<td>1.9</td>
<td>0.3</td>
<td>98.9</td>
</tr>
</tbody>
</table>

component and −125 μm ratio of the ores. Moreover, SiO₂ was set at 5.0 mass% and basicity was set at 2.0 by silica sand and lime stone. By the way, FeO average of sinter mix was 7.1 mass%. This sinter mix was charged into the hopper of the simulator and fed by 400 kg/min.

In this test, two conditions were carried out, with or without magnetic force. In former condition, the magnetic flux density was set at 0.12 T based on the calculation results of DEM model. In latter condition, permanent magnet plate was removed from the back side of the chute.

2.3.3. Evaluation Method

After charging, sinter mix was sampled in the five areas, which are 0 mm to 10 mm, 90 mm to 110 mm, 190 mm to 210 mm, 290 mm to 310 mm and 390 mm to 410 mm from the surface of bed by 1 kg and their FeO components were measured. Moreover, pot tests were carried out by the previous described cubic pot and their strength, yield and productivity were evaluated. In the pot tests, the suction pressure was kept at 9.9 kPa constantly. Yield was defined as the temperature at which tablet shape deviate from the dotted frame in the height direction staying the constant width and it was inferred that the Ca-ferrite tablet started to melt at 1 150°C using dense Fe₂O₃ substrate. But the contact area between Ca-ferrite and substrates decreased due to porous substrate and reaction rate decreased. As the result, its composition moved only up to CF² area and moved to the Hemi-Ca-ferrite (CF₂) which is the initial composition of the simulation. In former condition, the magnetic flux density was set at 0.12 T based on the calculation results of DEM model. In latter condition, permanent magnet plate was removed from the back side of the chute.

3. Experimental Results and Discussion

3.1. Melting Test of Ca-ferrite on Fe₂O₃ and Fe₃O₄ Substrate

Figure 4 shows the observation results of Ca-ferrite melting behavior on the Fe₂O₃ substrate during temperature increasing. The dotted frame in the figure showed initial outer frame of Ca-ferrite tablet and melting point was defined as the temperature at which tablet shape deviate from the dotted frame. The Ca-ferrite sample on the dense Fe₂O₃ substrate started to melt at 1 220°C as shown in (a)-4 of Fig. 4, the Ca-ferrite sample on the porous Fe₂O₃ substrate started to melt at 1 200°C as shown in (b)-2 of Fig. 4. It was inferred that this difference of temperature was caused by the difference of reaction ratio based on the difference of the surface area of substrates. Figure 5 shows the reaction route of Ca-ferrite on dense and porous Fe₂O₃ substrate in phase diagrams. Using dense Fe₂O₃ substrate, the Mono-Ca-ferrite (CF) which is the initial composition of the Ca-ferrite tablet started to react with Fe₂O₃ at 1 155°C and moved to the Hemi-Ca-ferrite (CF₂) in the phase diagram. After that, its composition moved into CF₂+Liquid area which is solid-liquid phase at 1 226°C and the liquid phase was generated. On the other hand, using porous Fe₂O₃ substrate, CF started to react with Fe₂O₃ at 1 155°C like dense Fe₂O₃ substrate. But the contact area between Ca-ferrite and substrates decreased due to porous substrate and reaction rate decreased. As the result, its composition moved only up to CF+CF₂ area and moved into CF₂+Liquid area at 1 205°C and the liquid phase was generated.

Next, the observation results of Ca-ferrite melting behavior on the Fe₃O₄ substrate during temperature increasing are shown in Fig. 6. As shown in (c)-3 of Fig. 6, the Ca-ferrite tablet started to melt at 1 160°C using dense Fe₃O₄ substrate. But, the Ca-ferrite tablet started to deviate from the dotted frame in the height direction staying the constant width and it was inferred that the Ca-ferrite tablet started melt at 1 150°C using porous Fe₂O₃ substrate as shown in (d)-2. It was thought to be caused by a reducing atmosphere in the furnace. Because, this test was carried out in the 7%CO-93%CO₂ atmosphere to avoid the oxidation of magnetite substrate. As a result, reduction of Ca-ferrite samples should be caused by this 7%CO-93%CO₂ atmosphere during the temperature increasing. Therefore, it is difficult to think that direct reaction between initial Ca-ferrite sample and magnetite substrate causes like hematite substrate.

It is well known that CF cause the following reaction in the 7%CO-93%CO₂ atmosphere to avoid the oxidation of magnetite substrate. As a result, reduction of Ca-ferrite samples should be caused by this 7%CO-93%CO₂ atmosphere during the temperature increasing. Therefore, it is difficult to think that direct reaction between initial Ca-ferrite sample and magnetite substrate causes like hematite substrate.

CF + 1/4CO = 1/4C2F2 + 1/2 CWF + 1/4CO₂ .... (1)

Here, C2F means 2CaO·Fe₂O₃ and CWF means CaO·Fe₂O₃. Figure 7 shows the reaction route of formula (1) and Fig. 8 shows the binary phase diagram of CaO–Fe₂O₃ systems. The reaction described in the formula (1) demands CO gas. If CO gas can penetrate into Ca-ferrite tablet and Fe₂O₃ substrate, Ca-ferrite react in the direction of an arrow described in Fig. 7 in the 7%CO-93%CO₂ atmosphere.
The CWF generated in this reduction reaction should react with iron oxides. As the result, temperature that initial melt generated should increase as shown in Fig. 8.

Thus, using the dense Fe$_3$O$_4$ substrate having higher reaction ratio than that of the porous substrate, the temperature to start to generate liquid phase increased. Moreover, the atmosphere. The CWF generated in this reduction reaction should react with iron oxides. As the result, temperature that initial melt generated should increase as shown in Fig. 8. Thus, using the dense Fe$_3$O$_4$ substrate having higher reaction ratio than that of the porous substrate, the temperature to start to generate liquid phase increased. Moreover, the
Ca-ferrite melts penetrated into the porous substrate before it spread, Ca-ferrite tablet also decrease its height with constant width.

Figure 9 shows the change of apparent contact angle of Ca-ferrite sample on the iron oxide substrates during temperature rising. The apparent contact angles were less than 90° using the all substrates, it indicated that the Ca-ferrite melt to each iron oxide substrate has good wettability.

3.2. Interface Reaction of Fe₂O₃ and Fe₃O₄ Substrates

Figures 10 and 11 show the cross-sectional EPMA mapping images of the dense and porous Fe₂O₃ substrates keeping at 1300°C for 0 min, 3 min and 10 min. Ca which substrates didn’t include initially was found continuously in (b)-3 and (b)-10 compared with (a)-3 and (a)-10. It indicate that Ca-ferrite melts penetrated along the pores of substrates. In comparison of the bottom EPMA images with the same time among (a)-3, (a)-10, (b)-3 and (b)-10, it was apparent that the reactions of porous substrate were faster than that of dense substrate. It was caused by the difference of penetration mechanism between dense substrate and porous substrate. Using the dense substrate, the interface movement was observed as the result of Fe₂O₃ dissolution into Ca-ferrite sample. On the other hand, using the porous substrate, the initial contact area between Ca-ferrite and Fe₂O₃ is small, but the contact area increased by penetration of Ca-ferrite sample at the middle term of reaction. As the results, reaction ratio increased.

Figures 12 and 13 show the cross-sectional EPMA mapping images of the dense and porous Fe₃O₄ substrates keeping at 1300°C for 0 min, 3 min and 10 min. The compositions of liquid phase were shown in the all substrates with the experimental temperature. As shown in (c)-3 and (d)-0, 20%CaO-74%FeO-6%Fe₂O₃ composition was shown.

![Fig. 10. EPMA mapping images of interface between CF sample and dense Fe₂O₃ substrate.](image1)

![Fig. 11. EPMA mapping images of interface between CF sample and porous Fe₂O₃ substrate.](image2)
in point A and 20%CaO-66%FeO-14%Fe$_2$O$_3$ composition was shown in point B. Based on the reaction route shown in Fig. 7, the reaction of porous substrate proceeded more than that of dense substrate. Because the reaction proceeded with Fe$_3$O$_4$ after the reduction reaction shown in Fig. 7, the compositions of liquid phase were shown in all substrates.

Figure 14 also shows the measurement results of penetration distance of Ca-ferrite into the iron oxide substrates by using EPMA. Using both iron oxide substrates, the penetration distance into porous substrate was longer than that of dense substrate. Because, using the dense substrate, the interface movement was observed as the result of melting reaction. On the other hand, using porous substrate, Ca-ferrite penetrated along the pores of substrates as previously explained. In comparison of penetration distance between Fe$_2$O$_3$ and Fe$_3$O$_4$ using the dense substrates, that of Fe$_3$O$_4$ was longer than that of Fe$_2$O$_3$ and it showed the

<table>
<thead>
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<th></th>
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<th>3 min</th>
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<tr>
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<td>(c)-3</td>
<td>(c)-10</td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reacted</td>
<td></td>
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<td></td>
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<tr>
<td>interface</td>
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Middle part of interfusion

Deepest part of interfusion

Low  High

<table>
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<th>0 min</th>
<th>3 min</th>
<th>10 min</th>
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<tr>
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<td>interface</td>
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</table>

Middle part of interfusion

Deepest part of interfusion

Low  High

Fig. 12. EPMA mapping images of interface between CF sample and dense Fe$_3$O$_4$ substrate.

Fig. 13. EPMA mapping images of interface between CF sample and porous Fe$_3$O$_4$ substrate.

Fig. 14. Penetration depth of slag sample melt as a function of annealing time at 1300°C.
Ca-ferrite reactive property with Fe₃O₄ is better than that of Fe₂O₃. On the other hand, the penetration distance of Fe₂O₃ was longer than that of Fe₃O₄ using the porous substrates. It is thought to be due to difference of sintering property of each substrate. Figure 15 shows the backscattered electron (BSE) image of porous Fe₂O₃ and Fe₃O₄ substrates. There were many pores in Fe₂O₃ substrate, but there are few pores in Fe₃O₄ substrate. Sintering of porous Fe₂O₃ substrate proceeded in the experiment described in section 2.1 and decrease of the number of pores decreased penetration distance from here onwards.

3.3. Calculation Results of DEM Model

Figure 16 shows the cross-sectional images of sintering bed calculated by the model. Green ball is particle D subjected magnetic force. Bigger particles A (red) and B (yellow) were segregated into lower layer of sintering bed in all calculation conditions. Particle A, B and C (blue) were not subjected magnetic force and particle size segregation was caused. On the other hand, segregation condition of particle D had the big difference between each condition. In the Case 1 condition (magnetic force: 0 N), particle C and D had no difference in size and density, and they were dealt as same type of particle in calculation. As the result,

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<thead>
<tr>
<th></th>
<th>Fe₂O₃</th>
<th>Fe₃O₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reacted interface</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>Middle part of interfusion</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>Deepest part of interfusion</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 15. BSE image of interface between CF sample and porous Fe₂O₃ and Fe₃O₄ substrate.

Fig. 16. Cross section view of charged bed with DEM simulation model.
particle D was found in the particle C distribution range. In the Case 2 condition (magnetic force: 0.005 N), particle D was found in the particle C distribution range as with Case 1. In the Case 3 condition (magnetic force: 0.05 N), upper segregation of particle D was found. In the Case 4 condition (magnetic force: 0.5 N), upper segregation of particle D was found.

Next, the application of proper magnetic force (0.05 N) calculated in the model to commercial plant was studied. In this model, particle size was set bigger than actual particle size and the number of particles was decreased to reduce calculation load. Therefore calculated magnetic force (0.05 N) was too big for actual particles. Then proper magnetic force was corrected by measuring the average weight of actual quasi particles falling into particle C and D used to the charging simulator. At first, size distribution of quasi particles sampled 1 kg was measured and 50 particles in the smaller 78% size range same as size range of particle C and D in the model was sampled randomly and measured its average weight. As the result, its weight was 0.1 g, and it was about 0.4% of the weight of particle D in the model. Therefore, $2.0 \times 10^{-4} \text{N}$ (0.4% of 0.05 N) was set as proper magnetic force to apply the acceleration of particle D to actual particle on the chute. In this study, the magnetic flux density applying this magnetic force to actual particles were calculated.

As the result of measurement for magnet plate used to charging simulator, it was confirmed that $A=25.6 \text{m/s}$ and $b=33.5 \text{m}^{-1}$. Magnetic susceptibility of quasi particle is also 0.004 (−) by measurement. The distance between magnet plate and chute to act the proper magnetic force ($2.0 \times 10^{-4} \text{N}$) for quasi particle was calculated by these parameters, then it was 23 mm and its magnetic flux density was 0.12 T. These parameter was set as magnetic conditions in this test, but proper magnetic condition were set for each raw materials because the content rate of magnetite fine differ according to quasi particle and magnetic susceptibility differ according to the grade of magnetite fine.

### 3.4. Charging Test Results by Charging Simulator

Figure 18 shows segregation condition of FeO in the sintering bed with or without magnetic force. However average of FeO component is 7.1 mass% in the sinter mixture, FeO component reached at 11.5 mass% in the surface part of sintering bed with magnetic flux density 0.12 T. It meant the segregation of magnetite fine in the upper layer. Moreover, FeO component decreased with depth from the bed surface. On the other hand, FeO component was higher in the upper layer without magnetic field and its segregation was not sharper than the condition with magnetic field.

<table>
<thead>
<tr>
<th>Table 4. Result of pot test.</th>
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<tbody>
<tr>
<td>With magnet</td>
</tr>
<tr>
<td>Tumble index (%)</td>
</tr>
<tr>
<td>Yield (%)</td>
</tr>
<tr>
<td>Sintering time (min)</td>
</tr>
<tr>
<td>Productivity ($\text{t/h} \cdot \text{m}^2$)</td>
</tr>
</tbody>
</table>
As shown in section 3.1, Ca-ferrite tablet started to melt on Fe$_2$O$_3$ substrate with lower temperature than on Fe$_3$O$_4$ substrate. Reduction atmospheres are formed at the beginning of sintering reaction by the combustion of coke breezes. Therefore, dense Fe$_2$O$_3$ layer was formed at upper side of sintering bed by segregation of magnetite fine. And Ca-ferrite melt formed with lower temperature. As the result, it prevented strength in the upper side of sintering bed from decreasing by the lack of heat. Moreover, it was shown that penetration distance of Ca-ferrite into Fe$_3$O$_4$ substrates was longer than Fe$_2$O$_3$ using dense substrate in section 3.2. Therefore, segregation of magnetite fine formed dense Fe$_2$O$_3$ layer, after that Ca-ferrite melt forming from lower temperature penetrated into the Fe$_3$O$_4$ layer and bonding each particles increase the sinter strength.

Hida et al. also reported that magnetite ore was able to be treated as heat source in the study of decreasing NO$_x$ in the exhaust gas of sintering machine. In this way, Fe$_2$O$_3$ oxidation heat by the segregation of magnetite fine to the upper side contributed increasing strength and yield.

It was concerned about magnetite fine decreases sinter productivity by the decrease of permeability of sintering bed. But, in this test, the productivity and sintering time was improved by upper segregation of magnetite fine as shown in Table 4. It was considered that increase of productivity was caused by selectively upper segregation of fine ore. Pressure drop in the sintering bed occurs at wet zone, reacting and melting zone. On the other hand, pressure drop of sinter cake zone was very small. Therefore, fine ore which is factor to decrease the permeability segregated to upper side of sintering bed and decrease of permeability was prevented by changing to the sinter cake in earlier stage of sintering reaction. As the results, the sintering time with upper segregation of magnetite fine was shorter than the time with homogeneous distribution of magnetite fine.

Control of segregation charging of magnetite fine can reduce the effect of production decrease with decrease of permeability and can increase sinter strength and yield as explained above.

4. Conclusions

The reactive property between Fe$_2$O$_3$ or Fe$_3$O$_4$ substrates with two porosities and Ca-ferrite melts was studied to utilize magnetite fine ore. Moreover, based on the results, the possibility of improving sinter productivity by control of segregation charging with magnetite fine was found. The detail is following.

1) Ca-ferrite melt had good wettability to either substrate hematite or magnetite. Moreover, melting temperature of Ca-ferrite changed depending on porosity of substrate. Penetration distance into Fe$_2$O$_3$ substrate was longer than that of Fe$_3$O$_4$ substrate using dense substrate. On the other hand, penetration distance into Fe$_2$O$_3$ substrate was longer than Fe$_3$O$_4$ substrate using porous substrate.

2) Magnetite fine was segregated to upper side of sintering bed by magnetic field on the chute. There was also proper range of magnetic force to segregate magnetite fine based on calculation results of simulation model.

3) Sinter strength and yield were improved by the segregation of magnetite fine to upper side of sintering bed. Because, dense magnetite layer was formed in the upper side of sintering bed and Ca-ferrite melted and penetrated easily in the magnetite. As a result, the lack of heat in the upper side of sintering bed was compensated by these effects.

4) Sintering time decreased and productivity increased by segregation of magnetite fine. It is because that permeability at middle and lower layer, which govern the productivity, were maintained by removing magnetite fines.

REFERENCES