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To improve sintering performance when using a high proportion of pisolitic ore, the flow behavior of the melt and moisture condensation during sintering were investigated. Melt fluidity decreased at higher pisolitic ore ratios, suppressing pore formation and agglomeration. However, an addition of mill scale improved melt fluidity, accelerating the agglomeration of the sinter cake and improving sinter yield. Bed permeability also deteriorated at higher pisolitic ore ratios due to increased moisture condensation, which decreases the void fraction in the sintering bed, but it was possible to reduce the total pressure drop and improve bed permeability by creating vertical slits. The gas flow rate in the slits was calculated at 1.8 times that in a conventional bed. Moisture condensation is reduced by this increased gas flow rate.

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Analysis of Sintering Behavior for Improved Sintering Performance in High Pisolitic Ore Operation*







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1 Introduction

In the production of sintered ore, the use of Australian pisolitic ore has gradually increased in recent years in response to the need for cost reduction in ironmaking and preparation for the depletion of the good quality hematite ore used in the past. However, various problems have appeared as a result of this trend, including reduced yield, strength, and productivity in sintering.^{1,2)}

As part of a fundamental study of the sintering property of pisolitic ore, a number of research projects have been carried out in connection with the formation of the melt and fluidity of the melt.^{3 8)} Although changes in the pore structure attributable to the fluidity of the melt are considered important for deciding the strength of sintered ore,⁹⁻¹¹⁾ measurement of such changes is experimentally difficult, and virtually no reports have been published in connection with pore structure changes due to the melt flow of pisolitic ores. Thus, the present situation is not necessarily characterized by progress in elucidating the causes of strength deterioration.

The permeability of the sintering bed also has an important effect on sintering productivity. It has been pointed out that the flow resistance of the moisture-condensed zone which forms after ignition increases markedly from that of the starting material and becomes a major impediment to the gas flow.^{12,13)} However,

Synopsis:

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because no reports have been presented on the condition of the moisture-condensed zone in high pisolitic ore operation, the effect of pisolitic ore on permeability has not been clarified.

Therefore, in order to study the causes of yield deterioration in high pisolitic ore operation, the authors developed a new hot stage X-ray CT device for sintering experiments, which is capable of observing the sintering process in the hot stage, and performed analyses of pore structure changes due to melt flow and of agglomeration. The effect of pisolitic ore on permeability was also investigated by examining the moisture-condensed state of the sintering material layer, and methods of improving yield and permeability were studied.

2 Experimental Device and Experimental Method

Figure 1 shows the hot stage X-ray CT device for sintering experiments. In order to investigate changes in the cross-section during the sintering process, a tube-detector rotating-type X-ray CT with a short photographic

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Schematic diagram of hot X-ray CT scanner Fig. 1 for sintering test

time was adopted. The X-ray tube voltage of the device

Table 1 Chemical composition of raw materials

						((mass%)
Material	C.W.	TFe	FeO	SiO_2	Al_2O_3	CaO	MgO
Mixture A	1.15	61.99	3.67	3.65	1.65	2.95	0.55
Ore Y	8.05	59.12	0.09	4.82	1.10	0.03	0.05
Mill-scale	0.20	73.96	15.20	0.23	0.06	0.86	0.10

Table 2 Raw mixture for sinter test

Raw mixture		A	В	C
Mixture A	(mass%)	100	60	- 55
Ore Y	(mass%)		40	37
Mill-scale	(mass%)			8
SiO ₂	(mass%)	5.0	5.0	5.0
Basicity		1.8	1.8	1.8
Coke ratio	(mass%)	4.0	4.25	3.98

is 130 kV, the tube current is 200 mA, and the time melt.15) In all cases, the limestone and silica sand conrequired to photograph one cross-sectional image is 2.8 s. The CT images obtained are transmitted to an image analyzer, where cluster analysis,¹⁰⁾ pore network analysis,¹⁴⁾ and melt fluidity analysis are performed. In cluster analysis, the CT value of sintered areas is set at 1 200 or over, continuous groups of picture elements having this CT value or higher are defined as clusters, and the area and number of these clusters is measured. In network analysis, areas with a CT value of under 200 are considered to be pores. Following segmentation of the image, a line image is produced by thinning the pores. The pore area of the image before thinning is then divided by the total line length to obtain a branch width which expresses the average thickness of the pores. The branch density, which represents the number of pore branches per unit of area is also obtained from the number of branches in the line image. In the melt fluidity analysis, two CT images having a time difference are segmented into a pore part and a solid part. The difference between the two images is obtained, and is considered to represent the change due to the melt flow. The amount of area change per unit of time, when the sum of the areas of the part changing from solid to porous (area S_1) and the area

of melt fluidity.

changing from porous to solid (area S_2) is divided by the

photographic time difference (t), is defined as the index

(Index of melt fluidity) = $(S_1 + S_2)/t \cdots (1)$

The pot wall and grate and the wind box used in these experiments were of carbon. In consideration of the limits of X-ray transmission, the diameter was set at 0.1 m and the height at 0.1 m. The main raw materials used in the experiment are listed in Table 1. The raw mixtures of sintering material are shown in Table 2. Ore Y was used as the pisolitic ore. The raw mixtures used in the sinter test were this company's standard material (raw mix A), which does not include pisolitic ore, a mix (B) in which 40% of raw mix A was replaced with ore Y, and a mix (C) in which 8% mill scale was added to raw mix B with the aim of improving the fluidity of the tents were adjusted so that the SiO₂ of the blended material was 5.0% and basicity was 1.8. The amount of coke was 4% with raw mix A; 4.25% with mix B, to compensate for the heat of decomposition of the combined water in ore Y; and 3.98% with mix C, the coke content being reduced by an amount corresponding to the heat of oxidation of the mill scale. Water was added to obtain a 7% water content when the material was mixed. During sintering, the suction pressure was held constant at 1.5 kPa. Sintering was considered complete when the exhaust gas temperature showed its highest value.

The measurements of permeability were made mainly using a pot $\phi 0.15 \times 0.4$ m high. An experiment in which a permeable slit was formed with the aim of improving permeability was also performed. In forming the permeable slit in the material bed, a vertical plate 0.02 m thick was placed in the center of the pot, and material was charged around the plate to a height of 0.15 m from the grate surface. After removing the plate, gauze was spread over the material, and additional material was then charged over the gauze. Sintering was performed under conditions of a constant gas volume (0.3 Nm³/min) and constant suction pressure (5.9 kPa). In this experiment, material B was used.

3 Experimental Results and Discussion

3.1 Melt Fluidity during High Pisolitic Ore **Operation and Changes in Sinter Structure**

Figure 2 shows the changes in CT images during the sintering process with material A. With the X-ray device, it was possible to observe the changes in the pore structure and the state of agglomeration. Image analysis was performed using these C1 images, and changes in the pore structure, melt fluidity, and agglomeration were quantified.

Figure 3 shows changes over time in the branch width during the sintering process. The branch width begins to

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Fig. 2 Changes of CT images of sinter cake during sintering process



Fig. 3 Changes of branch width of sinter cake with blending of pisolitic ore and mill-scale during sintering process



Fig. 4 Changes of index of melt fluidity with blending of pisolitic ore and mill-scale during sintering process

increase with the start of sintering, and reaches saturation before the completion of sintering. With raw mix B, the increase in branch width is delayed, and the final branch width is approximately 20% less than with raw mix A, suggesting that the incorporation of pores was suppressed. With raw mix C, the decrease in branch width was limited to 8%.

Figure 4 shows the changes in the index of melt fluidity over time. If attention is given to 150–250s, when sintering is considered to proceed with relative stability, the index of melt fluidity of raw mix B has decreased by



Fig. 5 Grain size distribution of sinter cake with blending of pisolitic ore and mill-scale



Fig. 6 Relationship between cumulative index of melt fluidity and mean nominal diameter of grain through sintering process

roughly by 40% in comparison with raw mix A. In contrast, the decrease was approximately 20% with raw mix C.

Figure 5 shows the grain size distribution of solids in the cross section of the sinter cake after the completion of sintering. Here, the grain size is the nominal diameter, and represents the thickness of the links between solids. In comparison with raw mix A, the sinter cake of raw mix B contained many small grains up to a borderline of 4 mm, and had a cake structure with few large grains. This fact suggests that the agglomeration of grains during sintering was suppressed with raw mix B. With raw mix C, the grain size distribution lies between that of mixes A and B. Thus, it appears that the addition of mill scale promotes agglomeration with high blending ratios of pisolitic ore.

The fluidity of the melt, while indirectly affecting the reactivity and fusion of the sintering material, can also be considered to have a large influence on densification and pore development due to rearrangement of the material grains.¹¹) Therefore, the relationship between melt fluidity and agglomeration was investigated. The relationship of the cumulative value of the index of melt fluidity and the average diameter of grains from the start of sintering until completion is shown in **Fig. 6**. Here, the average diameter is based on number-size distribution.



Fig. 7 Changes of pressure drop in sintering bed with blending of pisolitic ore during sintering process

The plot of the cumulative value of the average grain diameter and index of melt fluidity falls on the same curve regardless of the raw material conditions, confirming the close relationship between melt fluidity and agglomeration. From this fact, it can be thought that agglomeration proceeds simultaneously with changes in the pore structure due to the incorporation of pores, which accompanies melt flow, and that this process also depends on the fluidity of the melt. The foregoing discussion implies that the general phenomenon in which sintered ore strength is reduced when pisolitic ore is used in large quantity can be traced back to a reduction of the melt fluidity. It can also be understood that the addition of mill scale is effective in improving the fluidity of the melt.

3.2 Permeability in High Pisolitic Ore Operation

The pressure loss with raw mixes A and B was measured by inserting a pipe into the material during sintering under a condition of a constant gas volume (1.2 Nm³/min). A pot $\phi 0.3 \times 0.4$ m high was used, and pressure loss was measured between the heights of 0.200 m and 0.215 m. The results are shown in **Fig. 7**. With raw mix B, which contained a high proportion of pisolitic ore, the gas flow resistance increased in the moisturecondensed zone and sinter zone before and after the reaction zone. The increase in the gas flow resistance in the sinter zone was considered to be attributable to the delay in pore development, while the increase in the condensation zone was thought to be due to a difference in moisture condensation behavior.

To gain a clearer understanding of the condition of the moisture-condensation zone in the raw material during high pisolitic ore operation, an interrupted sintering experiment was conducted using a pot $\phi 0.15 \times 0.4$ high. The moisture distribution in the sintering bed was investigated with the results shown in **Fig. 8**. With raw mix A, the moisture content of the condensation zone was 7.3%, but rose to 7.8% with raw mix B. This increase in the moisture content was considered to be the cause of the increase in gas flow resistance in the moisture-condensed zone of the raw material.



Fig. 8 Moisture condensation in sintering bed with blending of pisolitic ore



Fig. 9 Pressure drop and temperature in sintering bed

Figure 9 shows the results of a measurement of the temperature distribution and pressure loss in the sintering bed under a constant gas volume when permeable slits were made in the sintering bed of raw mix B with the aim of improving this rise in gas flow resistance. It should be noted that these measured results were taken at the point in time when the thermocouple 0.25 m above the grate surface recorded its maximum temperature. When a permeable slit is formed, pressure loss decreases and permeability improves, but in particular, a large decrease in pressure loss was observed in the lower layer.

Next, Fig. 10 shows the changes in the gas volume velocity from the start of ignition, under a constant suction pressure. In comparison with an ordinary bed, the gas flow volume before ignition is large in the bed with the permeable slit, and this trend remains the same during sintering. In all cases, the gas flow volume decreased immediately after ignition, and then again increased in the second half of sintering.

Figure 11 shows the results of a measurement of the moisture distribution in the sintering bed when sintering was interrupted at the point when the thermocouple 0.25 m above the grate recorded its maximum temperature. The conditions other than the existence of a slit were

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Fig. 10 Change of gas volume velocity during sintering



Fig. 11 Distribution of moisture in sintering bed

identical. When the permeable slit was not formed, moisture condensation was observed in all regions, and the formation of a moisture-condensation zone was confirmed. When the slit was formed, moisture content was reduced in the vicinity of the slit (region A), but moisture condensation occurred in the area near the pot circumference (region B).

Based on the results described above, an investigation was made to determine the relationship between permeability and the gas flow velocity distribution in the bed when a permeable slit is formed. The two-dimensional gas flow velocity distribution in a small-scale test pot was calculated using the general-purpose fluid analysis program PHOENICS. In this calculation, the pressure loss in the sintering bed was obtained using Ergun's equation.¹⁶⁾

$$\Delta P/H = 150(1-\varepsilon)^2 \cdot \mu \cdot U/(\varepsilon^3 \cdot d_p^2) + 1.75(1-\varepsilon) \rho_g \cdot U^2/(\varepsilon^3 \cdot d_p) \cdot \cdots \cdot (2)$$

- $d_{\rm p}$: Particle diameter (m)
- II: Distance in sintering bed layer height direction (m)
- ΔP : Pressure loss (Pa)
- U: Gas velocity in layer (m/s)
- ε : Void fraction of layer
- μ : Gas viscosity (Pa · s)
- $\rho_{\rm e}$: Gas density (kg/m³)

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Fig. 12 Calculated velocity pattern of gas flow in the slit formed bed

Here, the following calculation was made assuming that the gas viscosity, μ , is 1.8×10^{-5} Pa s, the raw material particle diameter is 0.002 m, and the gas density, $\rho_{\rm g}$, is 1.3 kg/m³.

In the results of the test with the small-scale pot, the sintering bed gas flow volume before ignition at a suction pressure of 5.9 kPa was $0.73 \text{ Nm}^3/\text{min}$ without the permeable slit. From this result, the void fraction ε , was calculated at 0.34. On the other hand, the gas flow volume with the permeable slit was $0.78 \text{ Nm}^3/\text{min}$. Assuming that ε for parts other than the slit was 0.34, the ε of the slit was 0.41, this value being obtained by calculating the gas volume so as to agree with the observed results. This calculated result indicates that the space of the permeable slit is not simply an empty space having the same shape as the plate, but rather, that material flows into it to form a relatively porously packed material layer.

The gas flow volume after ignition decreases rapidly to $0.33 \text{ Nm}^3/\text{min}$ without the permeable slit and to approximately $0.41 \text{ Nm}^3/\text{min}$ with the slit. From the results shown in Fig 9, the pressure loss and layer thickness of the dry zone in the upper part, reaction zone, and sinter zone total are 3.5 kPa and 0.2 m, respectively. Using these values, the results of a calculation of the void fraction, made in the same manner as above, are ε = 0.25 for the raw material layer with no slit, and 0.40 with a slit.

Next, Fig. 12 shows the results of a calculation of the velocity pattern when a slit was formed in the sintering bed. When no slit was formed, the gas flow velocity was virtually uniform in the bed, at approximately 0.31 m/s, but when a slit was formed, the gas flow showed deviation. Namely, the gas flow velocity increased greatly, to 0.56 m/s, at points a and b in the figure, and decreased somewhat, to 0.28 m/s, at points c and d.

Figure 13 shows the relationship between the calculated gas velocity and the sampled moisture content of the raw material. From this figure, it can be thought that the moisture content of the raw material decreased as the gas velocity increased, the gas humidity was reduced relatively by the permeable slit, and moisture condensation was suppressed.

When no permeable slit is formed, the decrease in ε



Fig. 13 Relationship between calculated gas velocity and moisture content

of the raw material layer due to the moisture-condensed zone before and after ignition is 0.09. In the breakdown of this figure, the volumetric fraction of the condensed moisture and the contraction of the layer accompanying rearrangement of the grains¹²) can be considered. The volume of 0.5% for increased moisture corresponds to ε of approximately 0.02. The remaining decrease of approximately 0.07 can be attributed to contraction of the layer. In contrast, when a slit is formed, it can be thought that the suppression of moisture condensation by the slit prevents the above-mentioned reduction of the void fraction, and that this in turn improves permeability.

4 Results of Experiment with Commercial Sintering Machine

4.1 Yield Improvement in High Pisolitic Ore Operation

An experiment in which mill scale was blended with sintering raw material was carried out at this company's Mizushima Works No. 2 sintering machine with the aim of improving melt fluidity in high pisolitic ore operation. The high pisolitic ore was a 40% blend of pisolitic ore. The mill scale blending ratio was increased from 0% to 3% and 8%. The operation conditions were adjusted to ensure uniform productivity and bed height.

The operational data during the experiment are shown in **Fig. 14**. After the start of the experiment (mill scale addition: 0%), a decrease in yield was observed, but yield increased when mill scale blending began, and substantially the original level was recovered at a blending ratio of 8%. As described above, yield improvement by blending mill scale to improve melt fluidity was confirmed with a commercial sintering machine.

4.2 Permeability Improvement in High Pisolitic Ore Operation

Using the same No. 2 sintering machine, an experi-



Fig. 14 Operation results using mill-scale with a large amount of pisolitic ore



Fig. 15 Outline of the poromeric improvement machine

ment was carried out in which steel plates were inserted at the bottom of the raw material bed to form permeable slits. The sintering machine pallet width was 4 m. Nine plates having a thickness of 0.02 m were used. The operational data with and without insertion were compared by making it possible to move the inserted plates in the longitudinal direction of the sintering machine, as shown in **Fig. 15**. The operation conditions were adjusted so that the burn-through point (BTP) and bed height were uniform.

Figure 16 shows the trend in the operational data. The results confirmed that inserting the plates improved the gas flow and reduced the main blower suction pressure. Burnt lime consumption was reduced by a corresponding amount. When the gas flow was adjusted to obtain a constant level of productivity, the unit consumption of burnt lime decreased by $2 \text{ kg/t} \cdot \text{s}$. Con-

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Fig. 16 Effects of the slitting plates on sintering operation

versely, removing the plates from the bed resulted in a deterioration of the gas flow, and the unit consumption of burnt lime again increased.

The results described above confirmed that a broad improvement in the permeability of the sintering bed can be achieved with actual equipment by inserting plates vertically at the bottom of the bed.

5 Conclusion

A study of melt fluidity and the moisture-condensed zone was carried out with the aim of improving yield and permeability in sintering when using a high blending ratio of pisolitic ore. The following results were obtained.

- (1) When pisolitic ore is blended at a high ratio, the fluidity of the melt decreases, and pore development and agglomeration are delayed, which can be considered to result in a decrease in the strength of the sinter.
- (2) The addition of mill scale improves fluidity, thus reducing the delay in pore development and agglomeration.
- (3) In high pisolitic ore operation, the moisture content of the moisture-condensed zone increases; this results

in an increase in the gas flow resistance of the sintering bed, which deteriorates permeability.

- (4) When permeable slits are made at the bottom of the sintering bed, pressure loss is reduced and permeability improves. A calculation of the gas flow velocity distribution in the sintering bed showed that the void fraction in the area of the slit was 0.40, and flow velocity in the area is approximately 1.8 times higher than that in a uniform bed (without slits).
- (5) In high pisolitic ore operation, experiments with a commercial sintering machine confirmed that it is possible to improve yield by adding mill scale, and that permeability can be improved by inserting plates at the bottom of the bed in the ore feed section.

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