1. Introduction

Two significant environmental changes have affected iron making field in recent years. One is the drastic rise in raw material prices triggered by strong demand for steel products in the Asian market, and the other is the need to reduce CO2 emissions as a countermeasure against global warming. In response to these trends, high productivity and low reducing agent rate operation are required at the blast furnace. For this, it is important to achieve high productivity and high quality suitable for these types of blast furnace operation in sinter products. On the other hand, from the viewpoint of iron ore resources, the most significant change has been a decline in production of high-grade hematite ore and increase in production of porous limonite ore and marra-mamba ore in Australia, which supplies more than 50 mass% of the procured iron ore used in Japan. Increasing the blending ratio of porous iron ores has narrowed the proper range of the melting level in sintering operation. The conventional sintering process, which centers on use of high density hematite ore and melting with large heat inputs, cannot fully respond to the recent trend toward porous iron ores. As a result, deterioration of permeability and sinter strength has emerged as a problem for sintering.

Control of the quasi-particle structure is well known as an effective method for increasing sinter productivity and quality in an environment characterized by diversified iron ore resources and has been the subject of numerous reports to date. For instance, in examining the distribution of coke breeze in quasi-particles, Sawamura et al. reported that a coke breeze coating granulation technique was applied at Kamaishi No. 1 Sinter Plant, where it contributed to improved coke combustibility. However, this work did not consider the granulation property, permeability resistance, or destruction of quasi-particles. At JFE Steel's West Japan Works with an annual production capacity of 13.5 million tons have already introduced the new granulation process. The new process remarkably improves both the productivity and reducibility of sinter products in spite of the recent prevalence of inferior ores. In addition to improving the sintering operation, this granulation process also contributes significantly to improve blast furnace operation, including both higher productivity and lower reducing agent rate.

KEY WORDS: sintering; granulation; productivity; permeability; reducibility; limestone; coke breeze; coating; melt fluidity; pore structure.
separate granulation of high CaO quasi-particles and low CaO quasi-particles, which were then blended and sintered, but this process does not include limestone coating granulation, and the study did not consider destruction of the quasi-particles. Based on fundamental research, the present authors\(^4\) proposed that it is possible to increase sinter productivity and quality by controlling the melting reaction of iron ore, which is achieved by segregating limestone and coke breeze at the surface of the quasi-particles.

As outlined above, we recognize that there have been numerous reports on the quasi-particle structure itself, but few reports have examined coating granulation conditions considering quasi-particle destruction or an improvement mechanism involving melting behavior. Moreover, while there have been many empirical studies on the sintering operation, few reports have gone on to investigate the effect on blast furnace operation. Therefore, this paper will report on the development at a commercial plant of the new coating granulation process proposed in our prior report,\(^4\) covering the manufacturing conditions for the targeted quasi-particle structure at the commercial plant, the influence of the quasi-particle structure on the sintering operation, and the evaluation of blast furnace operation using the sinter product.

More specifically, this study focuses on the development of a coke breeze and limestone coating granulation technology at the above-mentioned commercial plant. It also describes the manufacturing conditions for achieving the target quasi-particle structure, the influence of this quasi-particle structure on commercial sinter production and sinter qualities, the influence of these sinter products on blast furnace operation, and the design of a new granulation process which utilizes existing commercial equipment.

2. Experimental Method

2.1. Equipment of Commercial Plant Test

In order to define the influence of coke breeze and limestone distribution in quasi-particles on a commercial sintering operation, coke breeze and limestone coating granulation equipment was installed at a commercial sintering plant. Figure 1 shows the process flow of the coke breeze and limestone coating granulation technology at JFE Steel’s Kurashiki No. 2 Sinter Plant.

This technology is characterized by segregation of coke breeze and limestone at the surface of quasi-particles consisting mainly of iron ore. The granulation procedure is as follows. First, the raw materials, which are mainly iron ores, are granulated at the main granulation line. Secondary coke breeze and limestone, which are transported by a separate coating granulation line, are injected at the end of the drum mixer by a high speed conveyor (50–300 m/min). The coating granulation time of coke breeze and limestone is the most important control factor in this process and is adjusted by changing the conveyor speed. For comparison tests, equipment for transportation of coke breeze and limestone through the main granulation line was also installed, as in the conventional process.

2.2. Experimental Method at Commercial Plant

In the commercial plant tests, the operation test using the new coating granulation method was conducted by transporting the coke breeze and limestone by a separate coating granulation line and injecting these materials at the end of the drum mixer. For comparison purposes, a conventional operation test, in which the coke breeze and limestone were transported together with the iron ore via the main granulation line, was also conducted.

Table 1 shows the experimental conditions at Kurashiki No. 2 Sinter Plant. The burned lime ratio, bed height, and moisture content were kept constant in the commercial plant test. Changes in permeability were adjusted using the pallet speed to maintain BTP (Burn Through Point). Here, BTP is the calculated position where the exhaust gas temperature of the 3 wind boxes shows its maximum temperature, assuming that the exhaust gas temperature forms an upwardly-convex parabola, when the length of the 3 wind boxes after the end of the sinter strand is considered to be 100%.\(^5\) This maximum temperature is defined as the BTP temperature. The temperature level in the sinter bed was adjusted using the coke breeze ratio (bonding agent ratio) to maintain the temperature at BTP between 330 and 370°C. To avoid deterioration of permeability in the blast furnace, operation conditions such as the pallet speed, bonding agent ratio, and others were set to control the −5 mm ratio in the sinter to less than 6.0 mass%. The iron ore blending conditions included 25 mass%, 35 mass%, and 75 mass% of low grade limonite ore, which has a negative influence on melting behavior. In addition to the above, the SiO\(_2\) content and CaO/SiO\(_2\) of the sinter products were adjusted to 5.1 mass% and 1.8, respectively, by controlling the blending ratio of limestone, Ni-slag, and silica stone.

Table 2 shows the granulation conditions in the experiments. The laboratory test and commercial plant test were conducted with a constant Froude number, occupied ratio,

![Fig. 1. Process flow of coke breeze and limestone coating granulation technology at Kurashiki No. 2 Sinter Plant.](image-url)
Table 2. Granulation conditions.

<table>
<thead>
<tr>
<th></th>
<th>Kurushima 2DL</th>
<th>Laboratory test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum diameter (m)</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Rotation speed (rpm)</td>
<td>4.0</td>
<td>8.2</td>
</tr>
<tr>
<td>Froude number (→)</td>
<td>1.9 × 10⁷</td>
<td></td>
</tr>
<tr>
<td>Occupied ratio (vol%)</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Drum length (m)</td>
<td>21.0</td>
<td>0.3</td>
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<tr>
<td>Total granulation time (s)</td>
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<td></td>
</tr>
<tr>
<td>Water content (mass%)</td>
<td>6.7</td>
<td></td>
</tr>
</tbody>
</table>

and total granulation time. Here, the time from charging into the drum mixer until discharge from the drum mixer was measured using iron ore which had been given a white coloration as a marker, and this time was defined as the total granulation time in the commercial plant. The Froude number and occupied ratio were defined by the following Eqs. (1) and (2).\(^6\)

\[
F = \frac{r \times (N / 60)^2}{g} \quad \text{...(1)}
\]

\[
\phi = 100 \times \frac{P \times T}{\pi \times \rho \times r^2 \times L} \quad \text{...(2)}
\]

\(F\) : Froude number (→)

\(r\) : radius of drum mixer (m)

\(N\) : rotation speed (rpm)

\(g\) : gravitational acceleration (m/s²)

\(\phi\) : occupied ratio (vol%)

\(P\) : processed amount of sinter mixture (t/s)

\(T\) : total granulation time (s)

\(\rho\) : bulk density (t/m³)

\(L\) : drum length (m)

The laboratory tests were conducted using two types of drum mixers (diameter 1 m and 2 m) to investigate the effect of scaling-up on improvement with this method. Here, the injection distance of the coating materials were calculated assuming free fall from the belt speed of the final belt conveyor in the coating granulation line. The coating granulation time was obtained by calculation from the above-mentioned coating mixture injection distance, total granulation time, and length of the drum mixer. When the test was stopped temporarily and the injection distance in the drum mixer was measured, the results showed close agreement with the calculated results, and virtually no mixing of the coating materials could be observed in the axial direction in the drum mixer. Furthermore, when the marker was charged intermittently to the drum mixer in the commercial plant and the mixing conditions in the drum mixer were investigated, it was found that there was virtually no mixing in the axial direction in the drum mixer. After charging the marker, the drum mixer was stopped several times and the position of the marker was checked. The results confirmed that the speed of material transfer in the drum mixer is virtually constant in the axial direction. Because the coating granulation time showed no large differences in the laboratory tests and commercial plant tests, it is considered that the slice test results with a short length drum mixer can provide a sufficiently close analogy to the test results in the commercial plant. Because the coating materials are injected by a high speed conveyor in commercial plant tests, the impact force on the granulated mixture during coating granulation is considered to be larger than in laboratory tests. However, based on the fact that substantially the same results were obtained when laboratory tests were performed while changing the injection velocity of coating materials, the effect of the impact force on the granulated mixture during coating granulation was thought to be slight. Accordingly, it is considered that similarity between the laboratory test and commercial plant test was materialized.

2.3. Experimental Method at Laboratory Tests

In the laboratory, granulation tests and sintering pot tests were conducted as described in our previous report.\(^6\) The granulation tests at the laboratory were conducted in batch form using two drum mixers of 1 m and 2 m in diameter. As granulation conditions, the Froude number and occupied ratio were fixed at the values used in a commercial plant, as shown in Table 2. Sinter productivity was evaluated by the sintering pot with an internal diameter of 300 mm and height of 400 mm, with the suction pressure set at 9.8 kPa. Sinter product was defined as sinter cake over 10 mm after crushing from a 2 m height one time, and sinter yield was calculated by the net weight of over 10 mm sinter divided by the total sinter cake weight. Sintering time was defined as the time from ignition to peak exhaust gas temperature. The details of measurement methods for quasi-particle size and sinter quality were described in the previous report.\(^4\)

2.4. Quasi-particle Measurement Method

In the commercial plant tests, quasi-particles were sampled on the belt conveyor at the exit of the drum mixer. The quasi-particle size and limestone distribution in quasi-particles were analyzed as described in our previous report.\(^6\) In addition, shrinkage of the sintering bed was measured at the sintering machine discharge point, and a direct shear test was conducted with quasi-particles of 2.83–4.76 mm before drying.\(^7\)

2.5. Sinter Product Measurement Method

Sinter products were sampled on the final conveyor of the sintering plant. Measurement items included not only the -5 mm ratio and FeO content in the sinter, but also the shatter strength index (SI, JIS-M8711), relative reducibility (JIS-RI, JIS-M8713-1:2000), and low temperature reduction disintegration index (JIS-RDI, JIS-M8720). In these tests, the sinter product samples in each test were sampled once an hour during the period of the experiment, for a total of 10 times, taking approximately 50 kg each time, and these were used as reduction samples.

For reducibility in the blast furnace, a measurement method in which the reduction temperature is set at 1 100°C and the reducing gas composition is set at CO/CO₂ = 50/50 (vol%) has been proposed, focusing on the region from the thermal reserve zone to the cohesive zone.\(^8\) However, it has also been reported that high temperature reducibility shows a high correlation with JIS-RI,\(^9\) and the reducing agent rate was reduced accompanying improvement of JIS-RI in a commercial blast furnace.\(^10\) Accordingly, although there are several problems with relative reducibility, including differences in the flow rate of the reducing gas and the reduction degree in the height direc-
measurements were made in conformance with simple JIS-M8713, Part 1 for all conditions, including the reducing temperature, reducing gas composition and flow rate, size of the sinter product, etc.

Where low temperature reduction disintegration is concerned, although cases in which there is no correlation between RDI and the reduction degradation degree measured with a blast furnace inner reaction simulator have been reported, it has also been reported that there is a rough correspondence relationship between RDI and permeability in the commercial blast furnace. Accordingly, in the present work, low temperature reduction disintegration was measured in conformance with the JIS method, which has been adopted as an operational control index in JFE Steel.

The mineral composition in the sinter product was quantified using a combination of a powder X-ray diffraction method and an image processing method. The pore structure of the sinter product was measured using a mercury porosimeter under high pressure, and the average value of 10 measurements was used in all cases. Details may be found in a previous paper by the authors. Softening under load test for these sinter products was done to study the melting and reduction behavior at blast furnace. The softening under load test was performed by charging 10–15 mm sinter product into a graphite crucible with an inner diameter of 100 mm so as to form a bed approximately 60 mm in thickness and enclosing the top and bottom of this layer with layers of 15–20 mm coke, and the gas flow rate was set at 30NL/min due to restrictions related to the apparatus. All other conditions, such as the heating-up conditions, gas composition, and load conditions were set in accordance with a previous report. The mineral composition, pore structure, and load softening condition of the product sinter were all sampled 10 times at 1 h intervals, and the average value of the sinter product was used.

Furthermore, it was analyzed the blast furnace operation before and after the application of this process, in accordance with RIST model. In the blast furnace operation analysis, as sintering operation conditions, the productivity and the bonding agent rate were controlled so as to maintain a substantially constant BTP and BTP temperature, as described in Sec. 2.2, and conditions other than the iron ore blending conditions, including the bed height and burned lime ratio, were set at constant values. Blast furnace operation was compared over a period of approximately 1 month before and after the application of the coke breeze and limestone coating granulation method.

3. Experimental Results and Discussion
3.1. Operational Results at Commercial Plant

Figures 2 and 3 show examples of the operational results when the coating granulation time was set at 60 s and controlled by adjusting the belt speed of the injection conveyer. As shown in Fig. 2, when the coke breeze and limestone coating granulation method was applied, the quasi-particle size increased, BTP decreased, and the permeability of the sintering bed improved. Furthermore, shrinkage of the sintering bed at the sintering machine discharge point was reduced from 86 to 72 mm by applying this method. Sinter productivity was improved without changing the ratio of 5 mm in sinter products by increasing the pallet speed to maintain a constant BTP. As shown in Fig. 3, because we estimated that use of the coating granulation method had resulted in a rise in the BTP temperature and excess heat in the sintering bed, the bonding agent ratio was reduced to keep a constant BTP temperature considering the load on the cooler. The quality of the sinter product showed no particularly significant change in the shatter strength index, but both the JIS-RI and JIS-RDI improved.

3.2. Contribution of Factors to Improvement Effect

Figures 4 and 5 show the influence of the coating granulation time on the improvement effect with this technology. As shown in Fig. 4, productivity showed the maximum value at 40 s. When the coating granulation time was reduced to below 40 s, the distribution of the coke breeze and limestone in the raw mixture was spotty and the sintering condition at the discharge point was uneven. As a result, the strength of sinter cake decreased, the return fine ratio increased, productivity decreased. Moreover, because genera-
tion of −5 mm fines after crushing increased. −5 mm fines were not removed by the screen in the sinter plant, and −5 mm ratio in the sinter product increased greatly. Conversely, when the coating granulation time was extended to 80 s, both permeability improvement and productivity decreased, and the reducibility of the sinter product also deteriorated. As a result, productivity showed the maximum value at a coating granulation time of 40 s. Thus, considering the −5 mm ratio in sinter and productivity, a coating granulation time of 40 s was adopted as the proper operation point. Although this proper operation point can be expected to change depending on the limonite ore ratio and other material blending conditions, within the range of these experiments, the maximum value of productivity was obtained in all cases when the coating granulation times was 40 s.

Figure 5 shows the distribution of Fe and Ca in the quasi-particles when examined with an electron probe micro analyzer. Here, in order to clearly detect the distribution of limestone in quasi-particles, we investigated the quasi-particles without nuclei ore in order to determine the limestone distribution in the fine ore layer. The outline of the quasi-particle is shown by the white line, because the element calcium in the resin was detected simultaneously. With a coating granulation time of 40 s, Ca from the limestone segregated outside the Fe from the iron ore. On the other hand, at 80 s, Ca fused in the quasi-particle, resulting in a structure similar to that obtained with the conventional method. The deterioration in productivity improvement and reducibility mentioned above was attributed to this change. In detail, it is thought that granulation and destruction of quasi-particles proceed simultaneously in the drum mixer. Consequently, the limestone and coke breeze which were distributed on the surface of the quasi-particles immediately after injection are physically absorbed into the quasi-particles when the coating granulation time is extended. This means that the granulation time falls within a proper range, which is determined by inhomogeneous sintering at the lower limit and collapse of the quasi-particles at the upper limit. It is also reasonable to assume that the proper range of the coating granulation time is influenced by impact forces, for example, at the junction of the conveyor belt from the drum mixer to the sintering machine. Therefore, the optimum range will differ at each sintering plant.

Figure 6 shows the effect of the granulation method on the mass ratio, CaO content, and free carbon content per each particle size in the raw mixture. From this figure, the weight ratio of the coarse quasi-particle size increased, and the CaO and free carbon contents in the fine particle size increased remarkably. It is easy to think that these fine particles were segregated by the surface of the coarse quasi-particles after feeding to the sintering machine, even if the fine particles did not adhere to the surface of the coarse part.
As the coating granulation time was extended, it is thought that CaO and free carbon were physically incorporated into the coarse quasi-particles, and as a result, the improvement effect of the coating granulation method was reduced.

Moreover, the investigation for the vertical CaO and free carbon segregation in the sintering machine confirmed that the contents of CaO and free carbon tend to increase approximately 0.2% in the uppermost layer by the coke breeze/limestone coating granulation method. However, when fluctuations in the operation are considered, this was not thought to have an important influence on sintering behavior.

**Figure 7** shows the effect of the limonite ore ratio on improvement of the quasi-particle size and sinter productivity. The vertical axis in the figure indicates the difference between the results with the coke and limestone coating granulation method and the conventional method at 60 s of granulation time. Although improvement of the granulation property decreased as the limonite ore ratio was increased, sinter productivity improved. Limonite ore is coarser and has higher porosity than hematite ore. Increasing the material particle size before the granulation line reduces the improvement effect of granulation by coke breeze coating. As the authors pointed out in the past, even though limonite is coarse, if porous limonite ore is blended in the sintering mixture, surface diffusion through the pores increases. As a result, the CaO/(CaO+Fe2O3) content of the calcium-ferrite melt decreases and the liquidus temperature rises. As melt fluidity deteriorates, permeability in the hot stage also deteriorates, leading finally to a decrease in sinter productivity. Although increasing the limonite blending ratio reduced the granulation effect in this work, segregating coke breeze and limestone at the quasi-particle surface by the new process also reduced the excess melt reaction of iron ore, resulting in a net improvement in productivity. Specifically, the reducibility improvement effect increased because the new process makes it easier to remain porous limonite ore during sintering, resulting in an increase in micro pores.

**Figure 8** shows the effect of the mixer diameter on improvement of the quasi-particle size and sinter productivity at the commercial plant and laboratory tests. From this figure, it is clear that both the granulation property and sinter productivity decreased when the mixer diameter was increased, irrespective of the method adopted. On the other hand, although the effect of the coke breeze and the limestone coating granulation method tends to diminish when the mixer diameter is increased, substantial improvement in comparison with the conventional method was confirmed with both diameters. The reduction in improvement with the larger mixer is explained by the fact that, although kinetic energy, which contributes to granulation, is unaffected by the mixer diameter, impact energy, which promotes destruction of the quasi-particles, increases with mixer diameter. In other words, quasi-particles which were not destroyed in a small mixer may be crushed in a larger mixer.

### 3.3. Influence on Sinter Productivity

Coating granulation tests were conducted separately with each of the raw materials in order to segregate the effect of coke breeze and limestone on improvement in productivity and reducibility with the new method. **Figure 9** shows the change of productivity with the respective granulation methods. Assuming the raw material blending conditions and bed height are constant, sinter productivity is determined by the pallet speed, depending on permeability in the sintering bed, and sinter yield correlates closely with the cold strength of the sinter cake. Figure 9 shows contour lines for sinter productivity, which were calculated from the bulk density, bed height, pallet speed, and yield with each granulation method. Compared with the conventional granulation method, permeability improved and the pallet speed could be increased significantly with coke breeze coating granulation. However, sinter yield decreased. With limestone coating granulation, yield improved slightly, even though the increase in pallet speed was smaller than with coating granulation of coke breeze only. With coating granulation of both coke breeze and limestone, sinter yield was the almost same as with the conventional method and the increase in pallet speed was maximized.
First, in order to examine the improvement of permeability by the coke breeze coating granulation method, a direct shear test of wet quasi-particles was conducted. Figure 10 shows a comparison of the quasi-particle strength with each granulation method. Methods of measuring the granulated material strength include the Brazilian test,[18] in which the strength of the granulated material itself is measured. However, we decided to evaluate the packed layer strength of the quasi-particles because quasi-particles are very fragile and tend to show wide variation in measured values. In Fig. 10, the shear stress in the packed layer is expressed by Eq. (3). The angle of internal friction and cohesion force can be calculated by the gradient and intercept on the Y axis in this figure, respectively.

\[ \tau = \sigma \tan \phi = C \]  

\( \tau \): shear stress (Pa)  
\( \sigma \): normal stress (Pa)  
\( \phi \): angle of internal friction (°)  
\( C \): cohesion force (Pa)  

It is considered that cohesion force was increased by the coke breeze coating granulation method in comparison with the conventional method, even though there was no great change in the angle of internal friction with the two methods. This increase in cohesive force is caused by an increase of quasi-particle strength due to the fact that the ratio of hydrophobic coke breeze[4] physically absorbed into the quasi-particles decreased. Here, the cohesion stress obtained with the direct shear test in this work evaluates the vertical resistance of 2.83–4.76 mm quasi-particles as such, when these are adjusted to the water content of 6.7%. However, contraction in the wet zone during the sintering process is a destructive phenomenon of the powder packed layer, which has a high water content of 9% and contains extremely fine un-granulated parts. Thus, it is not possible to compare the two phenomena in a simple manner as identical phenomena. Qualitatively, however, it was estimated that the coke coating granulation method improved the cohesion stress of the quasi-particles and thus improved permeability in the wet zone.[4] In the sintering process, it is thought that permeability was improved with the coke breeze coating granulation method because shrinkage was restrained in the wet zone.

With regard limestone coating granulation, we investigated the sinter product to determine the reason for the improvement of permeability and close correlation between yield and cold strength. Figure 11 shows a comparison of the Ca and Fe distribution in the sinter by granulation method when analyzed by electron probe micro analyzer.
3.4. Influence on Sinter Reducibility and Blast Furnace Operation

To investigate sinter reducibility, we performed an analysis using a reduction rate equation based on a one-interface unreacted core model in consideration of the following three stages: chemical reaction resistance at the unreacted core, diffusion resistance through the reduced shell, and mass transfer resistance through the gas film around the sinter.

\[
\frac{\frac{\text{Cb} - \text{Ce}}{t}}{\frac{r_0}{a_0}} = \frac{f}{\text{kc} \cdot (1 + 1/K)} + \frac{r_0(3f^2 - 2f^3)}{6 \cdot \text{De}} \nonumber
\]

\[
+ \frac{(3f - 3f^2 + f^3)}{3 \cdot \text{kf}} \quad \text{(4)}
\]

\[
f = 1 - (1 - R)^{1/3} \quad \text{(5)}
\]

Cb: CO gas concentration (mol/m³)
Ce: CO equilibrium concentration (mol/m³)
t: time (s)
r₀: spherical equivalent diameter (m)
a₀: O₂ concentration in sinter (mol/m³)
kc: chemical reaction constant (m/s)
K: Fe–FeO equilibrium constant
De: effective diffusivity (m²/s)
R: Reduction ratio
f: Relative thickness of reduced layer

Here, kf was calculated by the Ranz–Marshall equation. Using the mixed control plot, we analyzed the reduction ratio range above 33% and calculated the chemical reaction constant, effective diffusivity, and JIS-RI contour line of sinter produced by each granulation method. These results are shown in Fig. 14. Here, the JIS-RI contour line substituted the prescribed reduction ratio and reduction time (180 min) for Eqs. (4) and (5), and the relationship between effective diffusivity and the chemical reaction constant was obtained. As a result, compared with the conventional coating granulation method, the coke breeze coating granulation method mainly caused an increase in the chemical reaction constant and JIS-RI, while limestone coating
granulation not only caused an increase in the chemical reaction constant, but also resulted in improvement in effective diffusivity and JIS-Rl. It is assumed that these increases in effective diffusivity and the chemical reaction constant show the effects of the reduction in the magnetite layer and increase in micro-pores. However, because a simple evaluation of these effects would be difficult, further detailed study is necessary.

In addition, as shown in Fig. 3, application of the coke breeze and limestone coating granulation method improved JIS-RDI in spite of an increase in reducibility. The decrease in secondary hematite due to limestone coating granulation was considered to be one of the reasons for this phenomenon, as shown in Fig. 11. However, as we believed that crack propagation causes a reduction degradation phenomenon, we measured the tolerance to these cracks when hematite is reduced to magnetite and crack propagation characteristics of the sinter product. Figure 15 shows the relationship between the probability density function and crack length analyzed on the assumption that crack distributions follow Weibull distributions. The Weibull modulus and mode length of cracks calculated by Eq. (8), are also shown in Fig. 15.

\[
\log[-\ln(1-G(x))] = \log \beta + m \cdot \log x \\
g(x) = dG(x)/dx = m \cdot \beta \cdot x^{m-1} \cdot \exp(-\beta x^m) \\
x_m = (1/\beta)^{1/m} \cdot (1-1/m)^{1/m}
\]

\( x \): crack length (\( \mu \)m)
\( G(x) \): cumulative number of cracks (-)
\( m \): Weibull modulus (-)
\( \beta \): constant (-)
\( g(x) \): probability density function (-)
\( x_m \): mode length of crack (\( \mu \)m)

A Weibull modulus of approximately 5–20 is considered to be conventional for industrial ceramics, but here, \( m \) was larger than that for typical industrial ceramics because the hematite in this measurement is a natural mineral and already contains many cracks caused by thermal stresses associated with rapid heating and cooling during sintering. In comparison with the sinter product made by the conventional granulation method, the sinter product with the coke breeze and limestone coating granulation method has a short mode length of crack and shows little variation. This indicates that the sinter product with the coating granulation method has a structure with tolerance to cracks. Figure 16 shows the change in the pore size distribution and mineral composition in sinter produced by each granulation method. From this figure, the reasons for improved crack tolerance with the coating granulation method are considered to be a reduction in amorphous silicate, which easily propagates cracks, and the fact that crack propagation was reduced by micropores. However, the analysis of the respective contributions of each factor to RDI improvement is an issue for future study.

Figure 17 shows the influence of the granulation method on melting and reduction behavior under load. Compared with the sinter produced by the conventional granulation method, the sinter produced by the coating granulation method had high reducibility at around 900 to 1300°C, a higher beginning temperature for increasing pressure drop, and lower pressure drop. This improvement in high-temperature permeability is considered to be attributable to the following two reasons: (1) The remaining FeO melt at high temperature decreased due to superior reducibility at high temperature, and there were fewer blockades on the cohesive zone, and (2) micro pores remained in the sinter product and inhibited the cohesion of the generated

<table>
<thead>
<tr>
<th></th>
<th>Primary hematite (mass%)</th>
<th>Secondary hematite (mass%)</th>
<th>Magnetite (mass%)</th>
<th>Calcium ferrite (mass%)</th>
<th>Amorphous silicate (mass%)</th>
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<td>Coating method</td>
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<td>9</td>
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</tr>
</tbody>
</table>

Fig. 15. Changes of crack distributions in sinter with granulation method.

Fig. 16. Changes of pore size distribution and mineral compositions in sinter by coating granulation method.

Fig. 17. Influence of granulation method on the melting and reduction behavior under load.
Table 3 shows the influence of the granulation method used in the sintering process on blast furnace operation at Kurashiki No. 2 BF, when analyzed by RIST model. This analysis confirmed that, under the same raw material blending conditions and blast conditions, sinter product also improved. The following knowledge was acquired:

1. The operation test results at the commercial plant showed that sinter productivity improved due to improved permeability in the sintering bed. The reducibility index and reduction degradation index of the sinter product also improved.
2. The coating granulation time has a proper range, which is determined by the lower limit for homogenous sintering and upper limit for destruction of quasi-particles.
3. The strength of quasi-particles and permeability were improved by coke breeze coating granulation. Limestone coating granulation suppressed excess melting reaction of iron ore and reduced the Al₂O₃ and Fe₂O₃ contents of the calcium-ferrite. As a result, it was possible to improve sintering productivity without decreasing sinter strength. The sinter structure produced by limestone coating granulation was connected by high strength calcium ferrite bond between the iron ore particles.
4. Sinter produced by this process has excellent reducibility and permeability at high temperature because many micro pores remain, and consequently, the gas utilization ratio in actual blast furnace operation improves.

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