Influence of Coke Breeze Positioning on the Sintering Behavior of Pellets and Raw Material Bed with Embedded Pellets

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The influence of coke breeze positioning on the sintering behavior of pellets and raw material bed with embedded pellets was investigated. With increasing the coke breeze ratio in the green pellet made from ore and coke mixture fine of –125 μm, the tensile strength of the green and dried pellets decreased. Based on the evaluations under the green and dried pellet equations concerning particle bond, it was presumed these results were caused by the decrease in the contact points between particles due to the reduction of mixture fine’s specific surface area.

With increasing the coke breeze ratio in the nucleus pellet, the tensile strength of the burned pellets also decreased. From the change in the porosity up to 900°C, sintering was predominant to the tensile strength. In the temperature from 900°C to 1 200°C, the increase of strength became small by adding coke breeze in the nucleus pellet. It was presumed this result was caused by remarkable increase of void after coke combustion.

In the sintering of raw material bed with embedded the coke breeze coating pellet, the surrounding temperature of pellet increased and the large void was generated below the pellet. Based on the 2-dimensional numeric evaluation, it was found the heat amounts of the pellet and gas heated by coke combustion were transported to the region under the pellet where the gas flow rate was low. It was considered this heat concentration caused the remarkable melting and large void formation.

KEY WORDS: coke breeze; pellet; tensile strength; specific surface area; sintering; combustion; void.

1. Introduction

In recent years, the quality of iron ore resources has changed, as seen in increase of Al2O3 content and progressively decreases of ore size. However, it is expected that many new brand ores developed at present will be very fine concentrated by various separations. On the other hand, short supplies of high quality raw materials have become remarkable as a result of robust steel demand in Asia. Under these circumstances, technical development concerning more usage of low grade ores and fine ores in the sintering process of iron manufacturing at Japan and Asia, has been required.

Various technologies for using low grade ores and fine ores have been studied. These include an granulation technology by using a pelletizer for pellet feed ore,1) and the MEBIOS method, in which the large-sized particles made from low grade ore and arranged in the sintering bed.2,3) In these processes, the void fraction of the sintering bed was increased by mixed use of pellets or coarse particles in the raw material mixture, made it possible to improve sintering bed permeability and increase productivity. However, to satisfy both improvements of coarse particles strength and appropriate control of the pore formation in the bed for securing sinter yield and strength, the necessity of optimizing the carbon sources position in the sintering bed has been pointed out.3)

Several studies have examined the influence of the coke breeze positioning as on the granulation and combustion properties of pellets. For example, Miyashita et al.4) reported that the granulation property deteriorated and cracking became remarkable with increasing the amount of inner coke of pellets, whereas, in the pellets with a 2-layer structure, sinter strength was improved by increasing the content of coke in the surface pellet. Sakamoto et al.5) reported that coating coke breeze on the green ball surface made it possible to secure an adequate supply of oxygen to coke, and thereby enabled efficient coke combustion.

Pore formation in the bed embedded large particles was studied by Kasai et al.6) and Kamijo et al.,3) who reported that, when a gas impermeable region such as aluminum fiber disks or large particles was arranged in the sintering bed, coarse pores formed below that region.

Although past papers have presented detailed studies of the influence of coke breeze positioning on the granulation property and strength of pellets, those studies did not include a quantitative evaluation of pellet strength based on the physical
properties of the powder and pore formation in the sintering process. Moreover, the influence of the coke breeze positioning at coarse pellets in the sintering bed on pore formation after combustion had not been examined adequately.

Therefore, in the present research, the influence of the coke breeze positioning on pellet strength and pore formation in a sintering bed was studied from the viewpoint of the physical properties of the raw material powders and the combustion behavior of the coke breeze.

First, in order to investigate the influence of the coke breeze positioning on pellet strength, pellets with different coke breeze blending ratios were prepared. The tensile strength of the pellets after granulation, called as green pellet, and that of the green pellets after drying, called as dried pellet, were measured. Thereafter, the measured results were compared with the estimated values predicted from the physical properties of the mixed powders. Second, tensile strength, apparent specific gravity and porosity of the pellets burned under various temperature conditions were measured, and the influence of the temperature and porosity on tensile strength was discussed. Finally, in order to investigate the influence of pellets on sintering behavior of raw material bed with embedded pellets, the temperature near the gate and the influence of pellets on sintering behavior of raw material was discussed. Finally, in order to investigate the influence of the coke breeze blending, this test was performed without limestone. Initially, a mixed raw material consisting of ore and coke breeze was charged into a pelletizer, and the pellets granulated by pelletizing with water. The coating layer was then adhered on the nucleus pellets by gradually adding the raw material and water. The water content of the green pellets was 7.2–7.6 mass% in the case of T1 to T4 and 16.4 mass% in T5. Pellets with a size of 15–16 mm were used in the tensile test.

In order to obtain the tensile strength of the prepared green pellets, the relationship between the applied load P and compressive displacement u as P-u curve was measured using a displacement controlled-type material testing machine (model AGS-H, manufactured by Shimadzu Corporation), and the fracture load \( P_{\text{max}} \) was obtained. Compressive speed was set to 1 mm/min. The tensile strength of spherical test pieces was calculated using the following equation proposed by Hiramatsu et al.\(^7\)

\[
\sigma = \frac{P_{\text{max}}}{\pi r^2}
\]

\( \sigma \): tensile strength of green pellet (Pa)

\( P_{\text{max}} \): fracture load (N)

\( r \): particle diameter (m)

The coating structure of the green pellets was evaluated by micro X-ray CT observation.

Regarding the strength of green pellets, research by Tigerschiold et al.\(^9\) clarified the fact that the capillary force in the green pellet was the controlling factor of the strength, and Miwa et al.\(^9\) reported that this capillary force could be expressed by the function of the contact angle and the hydraulic radius of a powder. Therefore, in order to evaluate the capillary force when the coke breeze blending ratio in the nucleus pellet of the green pellet was changed, the infiltration rate of water was measured in accordance with the method proposed by Yokota et al.\(^10\) using mixed powders with various coke breeze blending ratios, and the hydraulic radius \( R_p \) was calculated using Eq. (2).

\[
W^2 = \frac{R_p \gamma_s \cos \theta}{2 \eta} \left( s \varepsilon \rho_l \right)^2
\]

\( W \): infiltration weight (g)

\( t \): time (s)

\( R_p \): hydraulic radius (m)

\( \gamma_s \): surface tension of water \((10^{-3} \text{ N/m}) = 72.8 \)

\( \theta \): contact angle between powder particle and water (°)

\( \eta \): viscosity of water \((10^{-3} \text{ Ns/m}) = 0.89 \)

\( s \): inner cross section area of column \((\text{mm}^2) = 78.5 \)

\( \varepsilon \): porosity of mixed powder (–)

\( \rho_l \): density of water \((\text{g/cm}^3) \)

Here, the porosity of the mixed powder \( \varepsilon \) was calculated using the following equation:

\[
\varepsilon = 1 - \frac{\rho_a}{\rho_s}
\]

\( \rho_a \): absolute specific gravity of mixed powder \((\text{g/cm}^3) \)

\( \rho_s \): apparent density of mixed dry powder \((\text{g/cm}^3) \)

Using the above-mentioned measured values, tensile strength was evaluated assuming that liquid fullness was

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**Table 1.** Chemical composition of Ore A (mass%).

<table>
<thead>
<tr>
<th>Combined Water</th>
<th>T. Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>1.99</td>
<td>67.8</td>
<td>0.66</td>
</tr>
</tbody>
</table>

**Table 2.** Chemical composition of coke breeze (mass%).

<table>
<thead>
<tr>
<th>Fixed Carbon</th>
<th>Volatile Matter</th>
<th>Total Sulfer</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke breeze</td>
<td>82.9</td>
<td>2.7</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**Table 3.** Blending conditions of green pellet (mass%).

<table>
<thead>
<tr>
<th>Blending ratio (mass%)</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleus pellet</td>
<td>Ore A</td>
<td>95</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Coke breeze</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Coating layer</td>
<td>Ore A</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Coke breeze</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
constant, using the strength equation (Eq. (4)) for agglomerates by water bridge, as proposed in a previous report.\(^9\)

\[
\sigma = \Psi \cdot P_c \hspace{1cm} \text{(4)}
\]

\[
P_c = 6 \cdot \frac{1 - \varepsilon}{\varepsilon} \frac{\gamma_c \cos \theta}{D_p} \hspace{1cm} \text{(5)}
\]

\[
\Psi = w \cdot \frac{1 - \varepsilon}{\varepsilon} \frac{\rho_c}{\rho_w} \hspace{1cm} \text{(6)}
\]

\(\sigma\): tensile strength (Pa)

\(\Psi\): fullness of liquid (–)

\(P_c\): inlet suction pressure (Pa)

\(D_p\): specific surface area diameter of particles (m)

\(w\): water content of green pellet (–)

\(\rho_c\): specific gravity of water (g/cm\(^3\))

The specific surface diameter \(D_p\) is expressed by the specific surface area \(S\) and the hydraulic radius \(R_p\), as shown in the following equations.\(^9\)

\[
S = \frac{6}{D_p} \hspace{1cm} \text{(7)}
\]

\[
R_p = \frac{\varepsilon}{1 - \varepsilon} \frac{1}{S} \hspace{1cm} \text{(8)}
\]

\(S\): specific surface area (m\(^2\)/m\(^3\))

2.2. Evaluation Method for Tensile Strength of Burned Pellet

For the preparation of burned pellets, green pellets were dried at 105°C for 24 h and charged into an electric furnace, and heated to the specified temperature (300, 500, 700, 900, or 1200°C) at a rate of 15°C/min, followed by holding at that temperature for 60 s, after which the pellets were discharged from the furnace and rapidly cooled. The fracture load was measured in the same manner as with the green pellets, and the strength of the dried pellets was evaluated by Eq. (1). Equation (9), using the specific surface area diameter, was derived for the tensile strength of the dried pellets,\(^11\) and the measured values and calculated values were compared, assuming that \(H\) is constant.

\[
\sigma = \frac{9}{8} \frac{1 - \varepsilon}{\varepsilon} \frac{H}{D_p^2} \hspace{1cm} \text{(9)}
\]

\(H\): adhesion force per contact point with adjacent particle (N)

2.3. Sintering Pot Test Method by X-ray CT

In order to clarify the influence of the various green pellets on the sintering process of raw material bed, sintering pot tests were performed in an X-ray CT, in which dried pellets were embedded in raw material bed. The dried pellets were prepared in which all coke breeze was contained in either the nucleus pellet as T1 or the coating layer as T4 in Table 3. The raw materials without pellets were the same in all cases. They were a South American ore as Ore A, Australian ore as Ore B, limestone, silica sand, return fines, and coke breeze, all of which were used in an actual sinter plant. The ores were sized to ~4.75 mm, and the other materials were sized to ~2.8 mm. Table 4 shows the blending conditions. Here, the blending ratio of return fines was set at 19.1 mass%, and the blending ratios of limestone and silica sand were adjusted so as to obtain a SiO\(_2\) content of 4.8 mass% and basicity as CaO/SiO\(_2\) of 1.9 in the sintered ore.

The raw mixture granulated with a drum mixer was charged into the carbon test pot (100 mm\(\phi\) × 100 mmH) shown in the schematic illustration in Fig. 1. Then, Two dried pellets of each type were embedded at the 50 mm height position in the test pot. In order to measure the temperature inside and outside the pellets, thermocouples were placed at the center of one green pellet and at a horizontal position as 5 mm from another pellet surface. Weight of charged raw mixture was constant, and exhaust gas flow rate was constantly controlled as 0.2 m\(^3\)/min in sintering. The X-ray CT images were analyzed in a region as 65 mm × 34 mm around the pellets that included the areas above and below the pellets. The imaging conditions and image analysis method were decided based on a previous report.\(^{12}\) The X-
ray CT images were binarized, and pores were converted to line images as branch by thinning processing. The branch width obtained by dividing the pore area of the image before thinning by the total line length of the branch was used in evaluation of pores.

3. Experimental Results

3.1. Tensile Strength of Green Pellets and Dried Pellets

Among the pellets prepared under the blending conditions in Table 3, Fig. 2 shows the P-u curves obtained from the compressive crushing tests of the T1 pellet containing 5% coke breeze in the nucleus pellet, and the T4 pellet containing 0% coke breeze in the nucleus. With increasing compressive displacement, the large fracture extended to the entire green pellet and a sudden drop in the load appeared in the P-u curve. The fracture displacements $u_a$ and $u_b$ were 0.29 mm and 0.35 mm respectively, and the fracture loads $P_a$ and $P_b$ were 18 N and 25 N respectively.

Figure 3 shows X-ray CT cross-sectional images of the green pellets, together with enlarged views near the pellet surface. The inside of the T1 pellet was observed as a homogeneous mixed body of ore and coke breeze, while mixed layer of ore and coke breeze coating peripherally around the nucleus pellet with thickness of approximately 0.3 mm was observed at T4 pellet.

As described above, differences in the fracture load were observed, depending on the presence of the coke breeze in the green pellets. Therefore, in order to estimate the tensile strength of green pellets with different coke breeze blending ratios, the infiltration rate of water was measured using mixed powders of the same blends as the nucleus pellets from T1 to T5 shown in Table 3. Figure 4 shows the time dependency on the square values of the infiltration water weight into the various mixed powders. The square values of the infiltration weight increased linearly with time course. Then, the hydraulic radius $R_p$ was calculated using Eq. (2) under assumption this linearity from 0 s to 150 s of infiltration time. Regarding contact angle $\theta$, some values have been reported that 84° for coke breeze obtained by infiltration method,13) 84–86° for graphite obtained by static drop method,14,15) and around 60° for hematite type ore obtained by infiltration method).16) In general, the contact angle of carbon materials tends to be larger in comparison with those of dense ores. Therefore, in the calculations of $R_p$, contact angles of 84° for coke breeze and 60° for ore were used, and the weighted average of the contact angle based on volume was used for the mixed powder of coke breeze and ore. Table 5 shows the calculated results of the hydraulic radius of mixed powders T1 to T5, together with other physical properties. The results showed that the hydraulic radius increased with increasing the blending ratio of coke breeze.

Figure 5 shows the measured tensile strength of the green pellets and dried pellets obtained using Eq. (1), and the calculated tensile strengths obtained using Eqs. (4) and (9). When the coke breeze ratio in the nucleus pellet was 8 vol% or more, the measured tensile strength of the green pellets

<table>
<thead>
<tr>
<th>Nucleus pellet</th>
<th>Real Density ($\rho$)</th>
<th>Void (%)</th>
<th>Wetting Angle ($\theta$)</th>
<th>Hydraulic Radius ($R_p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>88</td>
<td>4.39</td>
<td>39.9</td>
<td>0.12</td>
</tr>
<tr>
<td>T2</td>
<td>93</td>
<td>4.52</td>
<td>40.0</td>
<td>0.10</td>
</tr>
<tr>
<td>T3</td>
<td>97</td>
<td>4.66</td>
<td>41.1</td>
<td>0.07</td>
</tr>
<tr>
<td>T4</td>
<td>100</td>
<td>4.73</td>
<td>40.1</td>
<td>0.09</td>
</tr>
<tr>
<td>T5</td>
<td>0</td>
<td>1.85</td>
<td>45.1</td>
<td>0.68</td>
</tr>
</tbody>
</table>
decreased with increasing the coke breeze ratio, and this measured tendency was seen in the calculated values. The tensile strength of the dried pellets was maximum value at a 3 vol% coke breeze ratio in the nucleus pellet, and decreased with increasing coke breeze ratio over 3 vol%. This tendency in the measured values of dried pellets was also in good agreement with the calculated values.

3.2. Tensile Strength of Burned Pellets

Figure 6 shows the change in the tensile strength of the pellets burned at each temperature. As the coke breeze ratio in the nucleus pellets increased, the tensile strength of the burned pellets decreased. This tendency became more remarkable as the temperature increased. When the temperature was increased from 300°C to 500°C, the tensile strength of the burned pellets decreased slightly. However, when the temperature was increased from 500°C to 900°C, the tensile strength of the pellets increased. Moreover, the tensile strength of all pellets also increased when the temperature was increased from 900°C to 1200°C.

Figure 7 shows the temperature dependence on the apparent density of the burned pellets. The decrease in apparent density was attributable to volatilize of combined water when the temperature was increased from 300°C to 500°C. When the temperature was increased from 500°C to 900°C, the decrease in apparent density was estimated to be due to the progress of the coke breeze combustion. Above 900°C, apparent density increased with increasing temperature because the pore volume might be decreased accompanying the progress of sintering. The apparent density of the T1 pellet containing 12 vol% coke breeze in the nucleus pellet and burned at 900°C was 3.08 g/cm³ and 3.13 g/cm³ at 1200°C. In contrast, with the T4 pellet without coke breeze in the nucleus pellet, the respective values were 2.96 g/cm³ and 3.34 g/cm³. These results suggested that the progress of sintering had been accelerated in the T4 pellet.

Figure 8 shows the relation between the porosity of the burned pellets and the temperature. Up to 700°C, the porosity increased similarly in all of the pellets. However, at 900°C, the porosity in the T1 and T2 pellets increased a little. When the temperature was increased from 900°C to 1200°C, porosity decreased. In particular, with burning at 900°C, the porosity of T4 pellet was 38 vol% higher than T1 of 35 vol%. However, with burning at 1200°C, the porosity of T4 pellet was 32 vol% lower than T1 of 34 vol%.

Figure 9 shows cross-sectional photographs of the T1 and T4 pellets after sintering at 1200°C. In the T1 pellet containing 12 vol% of coke breeze in the nucleus pellet,
large pores were observed inside the pellet. Figure 10 shows the distribution of pore diameters obtained by the image analysis of binarized cross-sectional photographs in Fig. 9. In comparison with the T4 pellet, the percentage of large pores over 100 \( \mu m \) was higher in the T1 pellet.

3.3. Results of Sintering Pot Test

Figure 11 shows X-ray CT images around the T1 pellet embedded in the sintering bed and the temperatures inside and outside the pellet. The white areas in the X-ray CT images corresponded solid materials, and the black areas corresponded pores. According to the method in a previous report,\textsuperscript{11} the melting region was identified from the difference in 2 CT images taking within a short time. The broken lines in the figures were supposed as the frontline of the melting region, in the following, this line is called as melting front. As shown in Fig. 11, the temperature outside the pellet was maintained at around 60°C after ignition due to the formation of a moisture condensation zone in the raw mixture (Fig. 11(b)). As the melting front approached, the temperature outside the pellet increased (Fig. 11(c)). Thereafter, the outside temperature became the maximum as the melting front passing the pellet.

Figure 12 shows the results for the T4 pellet. Unlike the T1 pellet, the temperature outside the pellet achieved its maximum before the melting front passing (Fig. 12(c)).

Figure 13 shows the changes in the outside and inside temperatures of the pellets during sintering. The outside
maximum temperature in the case of pellet of T4 was higher, and also holding time over 1200°C was longer than T1. This was attributed to rapid combustion of the coke breeze coated on the outer surface of the pellet and was consistent with the results in previous reports.2,5)

Figure 14 shows the change with time course in the branch width of the sinter cake around the pellet. The branch width surrounding the pellet increased from 300 s after the start of sintering, and reached a saturation value after 600 s. Up to 500 s, T1 and T4 had similar pore growth rates, and no remarkable effect of coke breeze combustion could be seen. However, after 500 s, namely, when the melting front passed through the pellet, the pore growth rate of T4 increased, and the final branch width increased to approximately 22%, greatly exceeding that of the T1.

Figure 15 shows cross-sectional views of the sinter cake
4. Discussion

4.1. Influence of Coke Breeze Positioning on Tensile Strength of Green Pellets and Dried Pellets

From the results shown in Fig. 5, it was clarified that the measured values of the tensile strength of the green and dried pellets in each coke breeze blending ratio were corresponding well to the calculated values obtained using an estimation equation with the powder contact angle, porosity, and hydraulic radius. The influence of coke breeze on the tensile strength of green pellets and dried pellets will be discussed in the following.

Comparing the tensile strengths of green pellets of T4 without coke breeze in the nucleus pellet, and T1 containing 12 vol% of coke breeze, the measured tensile strength of T1 pellet was 1.4 times higher than the T4 pellet (T1: 0.24 kgf/cm², T4: 0.32 kgf/cm²). As factors on this difference of tensile strength, as shown in Table 5, showed that the porosity of only coke (T5) was larger than that of only ore (T4), and the hydraulic radius of the only coke was also larger. Accordingly, if the coke breeze ratio in a mixed powder was increased, the porosity and hydraulic radius of the powder were also expected to increase. However, at the coke breeze ratio of 3 vol%, the hydraulic radius was smallest. It was estimated that two types of powders were filled specifically in a high density due to the difference in the particle size distributions of the ore and coke breeze with this blending ratio. As a result, the contact point of fine particles may have increased. Accordingly, it was considered that the tensile strength of the dried pellets reached its maximum at a 3 vol% blending ratio of coke breeze in the nucleus pellet because a condition in which there were many contact points between the particles was also maintained after drying. Otsuka et al. evaluated the drying rate of water contained in green pellets and reported that the surface shape and specific surface area of pellet were the controlling factors of the maximum crushing strength of green pellet. This appeared to support the tendency of the results in the present research. Namely, the tensile strength of green pellets and dried pellets could be expressed well by the equations predominated by the particle specific surface area.

From the foregoing discussion, for the reason of the tensile strength decrease in green pellets and dried pellets accompanying increase of the coke breeze ratio in nucleus pellets, it was considered that the influence of the decreased number of contact points between the particles due to a decrease in the specific surface area of the mixed powders was greater than the influence of the wettability of water on coke breeze.

4.2. Influence of Coke Breeze Positioning on Tensile Strength of Burned Pellets

Based on the results presented in section 3.2, it was suggested that changes in the tensile strength of burned pellets were influenced by the progress of sintering and pore formation with combustion of coke breeze. Therefore, this influence was discussed in the case of T1 and T4 pellets because the large differences existed in the tensile strength, apparent density, and porosity changes.

As shown in Figs. 6 and 8, in the case at 900°C, the tensile strength of the T4 pellet became greater than that of the T1 pellet, although the porosity of the T4 pellet was larger than that of the T1 pellet. Here, the free carbon concentration remaining in the burned pellets was 2.5 mass% in the T1 pellet and 1.8 mass% in the T4 pellet. This meant that the amount of coke breeze combustion was smaller in the T1 pellet than in the T4 pellet. As noted by Sakamoto et al., in the T1 pellet containing the coke breeze inside the nucleus pellet, it was considered that this difference in coke breeze combustion was caused by the rate-limiting of the oxygen supply for carbon combustion. On the other hand, Tsuchiya et al. pointed out that the crushing strength was influenced by the number of contact points between ore particles, and was changed greatly if the bonding mode was different, even when porosity was the same.

Consequently, regarding the influence of coke breeze in the nucleus pellet on the tensile strength of burned pellets up to 900°C, it was estimated that the increased number of
contact points due to the progress of sintering was more dominant than the increased porosity due to extinction of coke breeze by combustion.

Next, in the case at 1200°C, as shown in Figs. 6 and 8, the porosity of the T4 pellet decreased 6 vol% and tensile strength increased by approximately 8 times in comparison with the values at 900°C. With the T1 pellet, porosity decreased by 1 vol% and tensile strength increased by approximately 5 times in comparison with 900°C. The residual free carbon in the burned pellets at this time was 0.24 mass% in the T1 pellet and 0.11 mass% in the T4 pellet.

Therefore, it was attempted to evaluate separately the influence of the increase in porosity due to extinction of coke breeze by combustion and the influence of the decrease in porosity due to progress of sintering from 900°C to 1200°C.

In the case at 900°C, even the T1 pellet still contained approximately 7 vol% of coke breeze, the increase in porosity due to extinction of coke breeze after burning at 1200°C was estimated to be 6.7 vol% from the difference in the residual free carbon concentrations at 900°C and 1200°C. Because the actual porosity decreased by 1 vol%, the decrease in porosity due to sintering could be estimated at 7.7 vol%. On the other hand, in the T4 pellet, the coke breeze was blended in the coating layer. Therefore, it was considered that the 6 vol% reduction in porosity was caused by the progress of sintering at 1200°C.

Based on these estimations, it was considered that the decrease in porosity due to sintering of the T1 pellet was larger than that in the T4 pellet. However, the tensile strength of the T1 pellet after sintering at 1200°C was smaller than that of the T4 pellet, and this could not be explained simply by the progress of sintering. In other words, about tensile strength, it was suggested that the influence of pores due to extinction of coke breeze by combustion was larger than the influence of sintering. Because the size of pores in the T1 pellet with the sintering at 1200°C was larger than the initial particle size of the coke breeze (~125 μm), as shown in Figs. 9 and 10, it was considered that pores combined after combustion of coke breeze and grew into larger pores. As a result, these coarse pores of this type would become the origin for fracture. This was corresponding to a report by Miyashita et al.9 that the increase of coarse pores due to combustion and gasification, and decrease in the strength of the sintered pellets with increasing coke breeze ratio in the nucleus pellet appeared simultaneously.

Accordingly, for tensile strength in sintering at 1200°C, it was estimated that the increased porosity due to combustion of coke breeze in the nucleus pellet was more dominantly than the progress of sintering of the ore.

4.3. Influence of Temperature around the Pellet on Pore Growth

As shown in Figs. 15 and 16, in the pore formation behavior of a sintering bed with embedded pellets, it was suggested that the coke combustion and, in particular, pore growth under the pellets was accelerated by the blending of coke breeze in the coating layer surrounding the nucleus pellet.

Therefore, the influence of coke breeze combustion on voids surrounding pellets was discussed. Regarding an experiment of sintering in the bed with embedded coarse particles, Kamijo et al.5 reported that, at surrounding the coarse particles, the gas flow rate became large due to the decreased packing density, the melt formation preceded, the melt infiltrated to the material layer, and porosity increased. Accordingly, with the T4 pellet in the present research, in addition to the effect of embedded coarse pellets in the sintering bed, it was estimated that many pores were ensured around the pellets because the melt formation proceeded due to the combustion of the coke breeze in the coating layer.

Kasai et al.2,6 reported that coarse pores formed under fibrous disks arranged in the sintering bed, and unburned parts could not be observed. From this, it was expected that certain heat transfer to the region below the pellets occurred.

Therefore, an analysis concerning the heat transfer behavior in the region below a pellet was performed using FLUENT. The model for analysis comprised a 2-dimensional square mesh in which 1 pellet was arranged in the center of a sintering bed with dimensions of 35 mm × 35 mm. It was assumed that heat transfer in the pellet was carried out as conductive heat transfer, and heat transfer from the combustion gas to the pellet surface occurred as convective heat transfer. Generation of the melt and the wet zone was important for the formation of gas paths. However, for simplification of calculation, these phenomena were not considered in the present analysis. The pellet diameter was set constantly at 15 mm, and the initial value of porosity was set at 0.25. The diameter of the quasi-particles comprising the raw material bed and porosity were assumed to be 3 mm and 0.4, respectively.

The blending ratio of the sintering mixture was as shown in Table 4, and the moisture content of the sintering mixture was set at 7.6%. The equation proposed by Ranz20 was used for the coefficient of heat transfer, and the value reported by Hotte21 was adopted as the combustion velocity of carbonaceous material. The coke breeze after combustion was assumed to disappear. In ventilation conditions, a constant wind speed of 0.4 m/s was given. The gas temperature was given as the measured temperature outside the T1 pellet shown in Fig. 13. A condition in which the combustion zone descended downward was simulated. Figure 17 shows the calculated results of the wind speed distribution and temperature distribution when the temperature in the sintering bed at the same height as the center of the T1 pellet reached 1200°C. Regarding the wind speed distribution, the flow speeds at the sides of the pellets were relatively high with both T1 and T4. The flow speeds were relatively low above and below the pellets, and the flows turned under the pellets and were crowded. Regarding the temperature distribution, in comparison with T1, the gas temperature around the T4 pellet increases rapidly due to combustion of the coke breeze on the pellet surface, and the temperature of the T4 pellet itself also reached a high temperature. Accordingly, it was estimated that the conductive heat transfer from the heated pellet and convective heat transfer of high temperature gas resulting from combustion of the coke breeze at the pellet surface to the low flow speed region below the pellet were carried out and the region below the pellet reached a high temperature and melt formation was promoted.

As described above, the present research clarified the thermal effect of adding a carbon source to the pellet, and confirmed that agglomeration was promoted by the supply
of heat from coke breeze combustion to the region below the pellet as a result of the gas flow detouring the pellet, which forms an not permeable part in the sintering bed.

5. Conclusion

It was investigated that the influence of the coke breeze positioning as homogeneous mixing in the pellet or coating on the pellet surface on the sintering behavior of the pellets and the sintering bed in which those pellets were embedded. The following conclusions were obtained.

(1) In green pellets and dried pellets prepared from ore and coke breeze adjusted to a particle diameter of –125 μm, tensile strength decreased with the increasing of the coke breeze ratio in the nucleus pellet. Based on strength equations for green pellets and dried pellets using water bridge between particles, as proposed in previous reports, it was estimated that this result was due to a decrease in the number of contact points between the particles accompanying a decrease in the specific surface area of mixed powders.

(2) The tensile strength of burned pellets decreased with increasing the ratio of coke breeze in the nucleus pellet, and this decreasing tendency became particularly remarkable with increasing the firing temperature. Regarding the influence of coke breeze in the nucleus pellet on the tensile strength of burned pellets up to 900°C, it was estimated that the increased number of contact points due to the progress of sintering was more dominantly than the increased porosity due to extinction of coke breeze by combustion. When the temperature was increased from 900°C to 1200°C, the amount of the increase in the tensile strength of pellets containing coke breeze in the nucleus pellet was smaller in comparison with pellets not containing coke breeze in the nucleus pellet. In this case, it was considered that the increased porosity due to combustion of coke breeze in the nucleus pellet was more dominantly than the progress of sintering of the ore.

(3) In sintering of a raw material bed with embedded pellets, combustion of coke breeze was promoted by the arranging coke breeze in the coating layer of the pellets. As a result, the temperature around the pellets and the internal temperature of the pellets increased, and large pores were formed below the pellets. In explaining this phenomenon, it was estimated that the conductive heat transfer from the heated pellet and convective heat transfer of high temperature gas resulting from combustion of the coke breeze at the pellet surface to the low flow speed region below the pellet were carried out and the region below the pellet reached a high temperature and melt formation was promoted.

REFERENCES