Dissection Investigation of Blast Furnace Hearth—Kokura No. 2 Blast Furnace (2nd Campaign)

Takanobu INADA,1) Atsuya KASAI,1) Kaoru NAKANO,1) Shusaku KOMATSU2) and Akinobu OGAWA3)

1) Corporate Research and Development Laboratories, Sumitomo Metal Industries, Ltd., 16-1, Sunayama, Kamisu, Ibaraki 314-0255 Japan. 2) Tokyo Head Office, Sumitomo Metal Industries, Ltd., 1–8–11, Harumi, Chuo-ku, Tokyo 104-6111 Japan. 3) Sumitomo Metals (Kokura), Ltd., 1, Konomi-cho, Kokurakita-ku, Kitakyushu, Fukuoka 802-8686 Japan. (Received on October 3, 2008; accepted on January 22, 2009)

Dissection investigation of blast furnace hearth was made at Kokura No. 2 Blast Furnace (2nd Campaign). Before blow-out, tracer response test was carried out in order to estimate the molten iron flow in hearth, and the measured data indicated that the depth of “effective” flow region of molten iron was extremely shallow. According to the result of the dissection investigation, the deadman was floating in hearth, and deadman coke was considerably degraded. Therefore, the poor permeability of the deadman is supposed to cause a downsize in the flow space of molten iron, which coincides with the prediction through the tracer response test. The numerical method to estimate the boundary shape of the deadman was developed by means of evaluating the stress field of the deadman in hearth. The calculated result was in reasonable agreement with the observed shape of deadman. In addition, based on the data obtained by analyses of the boring samples, the thermal equilibrium erosion shape of hearth refractory was evaluated by numerical simulation, and a good agreement to the observed shape was found.

KEY WORDS: blast furnace; hearth; dissection investigation; molten iron flow; erosion of refractory; deadman; less permeability region; numerical simulation.

1. Introduction

After the movement of large-sizing the inner volume and downsizing the number of furnaces, which occurred around the 1980’s in Japan, the furnace life extension has become one of the most important issues in blast furnace operation,1) since a huge investment is required to reline or rebuild a furnace. With the exception of scheduled blow-out based on a prior campaign plan, the furnace life is judged on the capability to keep the demand of production within ordinary maintenance activities. Recently, the technology for repairing inside the furnace, especially for the area above tuyere level, has developed significantly, such as replacing stave coolers and gunning castable refractory by means of the emptying operation technique. And these technologies have contributed to elongate the campaign life of blast furnaces up to over 10 years.1,2) However, as for the damage of the hearth area, which is occupied with molten iron, slag and coke, there is no effective way to empty and repair during a campaign. Therefore, the furnace life is supposed to be finally controlled by the damage of the hearth area.

The damage of the hearth area means the erosion of hearth refractory. Through dissection investigations of blast furnaces, which were carried out in the ’80s and the ’90s, the features of hearth erosion were found to be various, such as “bowl-shaped” erosion profiles3–5) and “elephant foot shaped” ones.6–9) Figure 1 shows the effect of molten iron flow on hearth erosion profile estimated by means of numerical simulation,10) including isothermal lines and assumed deadman profile. This figure consists of two simulation results. The left-hand side of this figure shows the estimated erosion profile in case that only conduction heat transfer in hearth was taken into account, while the right-hand side is the result in case that convectional heat transfer induced by the molten iron flow was also taken into account. Therefore, the molten iron flow brings heat into the hearth, and then hearth refractory is exposed to high temperature iron and is eroded through thermo-chemical solution such as carbon dissolution into molten iron or melting. This process is supposed to be affected by the inner hearth state, such as permeability distribution, as well as refractory property and layout. As for the inner state of the hearth, some investigations report that deadman coke was observed floating in hearth metal and various materials such as Ti bear and kish graphite were found in the hearth bottom.
On the other hand, many analyses have been made on heat load of hearth in operation, and then, it was found that the heat load fluctuates for the duration of operation and the distributions of heat load in hearth, as well as the fluctuation behavior, are different among furnaces. Through analysis about transition of the heat load based on the fundamental experiment and the result of dissection investigation of Mizushima No. 4 blast furnace, Sawa et al.\textsuperscript{11} state that the poor permeability area exists in heath deadman and its distribution affects the heat load through the molten iron flow and the drainage condition.

Meanwhile, many researches by use of numerical simulation have also been made on the relationship among inner hearth condition and heat load as well as molten iron flow, and discussed the effect of the lower boundary level and permeability distribution of deadman in hearth.\textsuperscript{12–15} Though, these works didn’t go beyond the “case study” level, since it was too difficult to estimate and specify the packing condition of the hearth as a calculation condition, theoretically. Recently, Nouchi et al.\textsuperscript{16} applied a numerical simulation based on the discrete element method (DEM) to investigate the deadman behavior in the hearth. In addition to estimating the lower boundary shape of deadman, in other words, the coke free space in the hearth, they discussed the replacing mechanism of the deadman, such as the flow pattern and the less permeability layer formation, with reference to the dissection investigation of Mizushima No. 4 blast furnace.

As a matter of course, the inner hearth condition of the real furnaces can be observed only through the dissection after blow-out. Then, taking the complexity and variety of hearth phenomena mentioned above into account, therefore, the knowledge about the inner hearth phenomena is still not sufficient to understand and control.

In this paper, the results of the dissection of Kokura No. 2 Blast furnace, which was carried out from the viewpoint of clarifying the inner state as well as the refractory erosion, are described. And, by use of numerical analysis, the inner hearth phenomena are discussed with relation to the heat load and refractory erosion of blast furnace hearth.

2. Overview of the Operation of Kokura No. 2 Blast Furnace

Kokura No. 2 Blast furnace started 2nd campaign in 1982 and finished in 2002. Figure 2 shows the furnace profile. The inner volume of the furnace is 1 850 m\(^3\), the number of tap hole was 3, and that of tuyere was 28.

Figure 3 shows the transition of production and hearth brick temperature for the last 5 years to blow-out. In this figure, it is noticeable that the transition of the heat load of the hearth can be categorized into two periods, that is, of indicating lower heat level and higher level, as denoted by circles. According to the previous works as mentioned above, the inner hearth conditions related to these periods are supposed to be extremely different from one another. Kokura No. 2 Blast furnace was blown-out in the period of lower heat load, while it suffered the maximum heat load in 1998, as denoted by “A” in Fig. 2.

3. Contents of Dissection Investigation

The dissection of the hearth of Kokura No. 2 Blast furnace was made by use of core-boring after blow-out without a salamander tapping. Prior to the blow-out, additional tests were made as shown in Table 1. The tracer response test was carried out to get the information about the depth of “effective” flow region of molten iron and determine the appropriate positions for core-boring. Mn ore charging test is to identify the stagnant or solidified region of molten iron based on the Mn concentration of the sampled metals.

4. Results

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Figure 4 illustrates the test. Cobalt oxide, which was used as the tracer material, was injected through a certain tuyere with hot blast. Then, the tracer, which was reduced

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to metallic Co in the furnace, was detected in the drained iron through the specified tap hole. And the time difference between start of injection and appearance of the tracer in the iron was regarded as a response time of the tracer.

In order to get the effective information, appropriate test conditions were examined to keep the following requirements: ① it is possible to catch the response peak of the tracer within one tap-operation which takes about 3 h; ② the peak concentration of the tracer in drained iron is sufficient to detect; and ③ the test is capable to estimate “effective” flow region in the hearth which depth is at least less than 3 m. Table 2 and Fig. 5 show the obtained conditions for tracer response test through several case studies by use of numerical simulation.

The tests were carried out on 4 cases in the last month before blow-out. The results indicate that the observed response times were distributed within 20 to 30 min, except for CASE-2 in which result was a little bit longer, as shown in Fig. 6. On the other hand, by use of numerical simulation, the effect of the depth of “effective” flow region on the tracer response time was evaluated on the basis of the hearth condition shown in Fig. 4. Figure 7 shows the results and the observed data is also indicated there. According to this figure, the “effective” flow region was supposed to be extremely narrow, and a less permeability material, which obstructed the molten iron from flowing down to the lower area, was suggested to exist in the hearth. Thus this estimation corresponds to the lower heat load of the hearth before blow-out, as shown in Fig. 3.

4.2. Mn Ore Charging Test

With iron ore burden, Mn ore was charged from the blast furnace top. In making a test schedule, a sufficient time to replace all over the hearth with Mn involved molten iron was required. Taking the pig production before blow-out into account, the test period of Mn ore charging was decided to be 3 days by use of numerical simulation. Figure 8 shows the transition of Mn concentration of the output metal, which was kept up nearly to 1% for 3 days before blow-out.
sponse test into account, the vertical positions of core-boring were intensively placed near the tap hole level and near the hearth bottom level, respectively. And the total number of core-boring points was 13.

### 4.4. Inner Condition of the Hearth

Based on the analyses of the boring samples, the erosion profile of hearth refractory and the inner hearth condition of Kokura No. 2 blast furnace were illustrated in Fig. 9. According to this figure, the erosion profile looks bowl-shaped and coke-free metallic layer exists at the bottom of the hearth, therefore, the deadman coke is floating in the hearth material. Photo 1 and 2 show the cross sectional views of the typical samples. While the coke-free metallic samples have glossy surfaces, as shown in Photo 2, the deadman samples contain metal iron and coke particles. As shown in Photo 1, it is noticeable that the coke particles are disintegrated into about 2 mm or smaller size. Therefore, the permeability of the deadman is supposed to be extremely poor, and obstructs the molten iron flow, which corresponds to the results of tracer response test mentioned above. Further discussion about the effect of the observed deadman condition on the heat load of hearth at blow-out will be made in the following chapter.

### 4.5. Properties of the Inner Materials of the Hearth

(1) **Bulk Density**

After the core-samples, which contain the inner materials, were cut down to size of about 1,000 to 1,200 mm, the bulk densities were measured. Figure 10 shows the bulk density distribution of the inner hearth materials. The bulk density of the deadman which includes metallic material was distributed within $2.2 \times 10^3$ to $4.9 \times 10^3$ kg/m$^3$, and increased downwards, depending on the metallic content. Consequently, the average value of the deadman was estimated to be $3.54 \times 10^3$ kg/m$^3$.

However, estimating the void ratio of the deadman, which corresponds to the volume ratio of the inter-particle space, in other words, the flow space for molten iron, failed. The reason for this is that the particle size in the deadman was extremely small, as mentioned above. In addition, according to microscopic observation, metallic iron penetrates into the pore of coke particle in deadman. Therefore, metallic iron exist in both the inter-particle space and particle pore, though, it was too difficult to distinguish the volume of inter-particle metal from that of in-pore metal.

(2) **Heat Conductivity**

As for the inner material samples including deadman, the measurements were made based on the comparative measuring method (JIS-R2618) at room temperature, while the
hot wire method (JIS-R2616)\textsuperscript{17} was applied for the metallic samples and measurements were made at temperatures up to 700°C.

The results are shown in Fig. 11 and Fig. 12. The heat conductivities of the deadman samples were distributed within 6 to 9 W/m·K, thus, they lay between the heat conductivity of metallic iron and that of coke. The measured values correlate to the bulk densities, as shown in Fig. 11, therefore, the heat conductivity of the deadman is supposed to depend on the metallic content of the deadman. On the other hand, as shown in Fig. 12, the measured values of the metallic samples are larger than the measured value of cast iron, as well as the literature values.\textsuperscript{18}

(3) Distributions of Mn and Ti

Figure 13 shows the observed Mn distribution in the hearth metal. As mentioned above, Mn content in output pig iron was increased up to about 1% for 3 days before blow-out in order to replace the molten iron in the hearth. According to the figure, metal of high Mn content was observed only around tap hole level. Therefore, the flow region of molten iron in the blowing-out period was supposed to be localized in tap hole level, and the other iron of the hearth was supposed to be stagnant or solidified. This supposition coincides with the results of the tracer response test and with the observed condition of deadman samples.

The Ti distribution in the hearth is shown in Fig. 14. On the whole, Ti content in the hearth material is very low, around 0.02%, while more than 0.1% is found in a certain part of the deadman. Photo 3 shows the microscopic image of the Ti bearing part. Many rectangular shaped crystals can be found there and its components are T, C and N. The reason why less Ti bearing material was found than previous investigations seems to be related to the fact that less carbonous refractory was exposed to the hearth metal.

5. Discussion

5.1. Mechanics of the Deadman Sinking in the Hearth

As mentioned above, the deadman was floating in the hearth at blow-out. The sinking depth of deadman in the hearth depends on the balance of forces acting on the deadman, that is, buoyant force by molten iron and downforce by gravity of its own and the moving bed above it. And the sinking depth closely relates to the appearance of coke free space in the hearth, which has an influence on the molten iron flow and hearth erosion. Therefore, it is important for understanding the hearth phenomena to estimate the condition of the deadman in hearth, such as the level and the shape of the lower boundary in the hearth.

However, the method applied in the previous works, such as DEM, is not suitable for practical use, since it requires heavy computing. In this work, the alternative simulation method based on the continuum modeling was developed. That is, the stress field analysis based on the rigid plastic theory which Takatani \textit{et al.}\textsuperscript{19} developed for a blast furnace simulation was applied. Although the target of evaluation is the balance of forces acting on the deadman, the stress field analysis was applied for the whole of the inner furnace as well as hearth, in order to eliminate the ambiguities originated from boundary condition setting. The formulation is as follows.

The equations of continuum and motion are shown in Eqs. (1) and (2), respectively.

\[
\frac{dp}{dt} + \rho \frac{\partial v_i}{\partial x_j} = R_w \quad \text{(1)}
\]

\[
\rho \frac{dv_i}{dt} + v_j R_w = f_i + \frac{\partial \sigma_{ij}}{\partial x_j} \quad \text{(2)}
\]

The term \( f_i \) in Eq. (2) denotes external force, which corresponds to the buoyant force by molten iron in hearth area and the drag force by gas flow in the draft area of the furnace, as well as gravitational force. Equation (3) is Drucker–Prager’s equation used as the yield condition, then the corresponding constitution equation is shown in Eq. (4).
\[ \alpha \cdot \sigma_{ij} + \frac{1}{\sqrt{2}} s_{ij}^2 s_{ij} = Y \]  \hspace{1cm} (3) \\
\[ s_{ij} = \frac{\sqrt{(s_{mn} s_{mn})}}{\sqrt{(\sigma_{ij} \sigma_{ij})}} \]  \hspace{1cm} (4)

where

\[ \sigma_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \]  \hspace{1cm} (5) \\
\[ s_{ij} = \frac{1}{3} (\sigma_{kk}) \delta_{ij} \]  \hspace{1cm} (6) \\
\[ \epsilon_{ij} = \frac{1}{3} (\sigma_{kk}) \delta_{ij} \]  \hspace{1cm} (7)

Based on the above formulation, the evaluation of the stress field is performed by use of the finite element method (FEM), and rotational symmetry in respect to the furnace axis is assumed.

To confirm the validity of this method, the lower boundary profile of the deadman was estimated and compared with the observed one as shown in Fig. 9. Since the heat load of the hearth was low in the period of blow-out, the layer thickness of solidified iron was examined in advance. Figure 15 shows the result, which was estimated based on the measured temperature at the center of hearth bottom by use of one-dimensional heat transfer calculation. At the time of blow-out, the hearth is supposed to be extensively covered with the solidified layer, and accordingly the deadman was supposed to be already frozen and unmovable. Therefore, going back to the time when the deadman was supposed to be free to move, May to June of 2000 was selected for the target period for the estimation, as denoted by “B” in Fig. 3. The operation condition of the period is shown in Table 3. The detailed procedure is as follows.

At first, the gas flow simulation was made, and the bulk density distribution in the furnace, except for the hearth area, was determined to fit the observed data of gas pressure at the wall, as shown in Fig. 16. The results are listed in Table 4. And the distribution of drag force by gas flow was also evaluated in the simulation. On the other hand, as for the hearth area, the observed data was used as the bulk density of the deadman, and the buoyant force by molten iron was taken into account as the external force in Eq. (2). The molten iron level was assumed to be located 0.6 m above tap hole. Table 5 shows the calculation conditions.

In addition, the material annihilation areas, which cause burden descent, were set up in front of tuyere and at the melting zone of ore, and the annihilation rates which correspond to \( R_a \) in Eq. (2) were determined according to the operation condition shown in Table 3.

In the FEM calculation, quadrangular elements were used. Initially, the deadman was sunk to an arbitrary level in the hearth, then the lower boundary of the deadman was successively updated in the reiterative calculation process so that the stress on the boundary surface converge to zero. At each reiterative step, the calculation grid was re-generated according to the updated boundary shape. As for boundary conditions, on the deadman surface, normal component of particle velocity was fixed at zero, while slip condition was applied for tangential direction. And it was assumed that there was no upward stream of coke flow just under the raceway.

Figure 17 shows the estimated result of the lower boundary shape of the deadman. Comparing the observed result through core-boring, which is also drawn in the figure, rea-
sonable agreement can be found, therefore this method is valid and suitable for a practical use, since it takes about 1 or 2 h to obtain a solution by an ordinary PC.

The lower surface profile of deadman in hearth were discussed in previous works. By use of a 2-dimensional cold model experiment, Shibata et al.\(^\text{14}\) state that the lower surface has a slope inclined toward periphery with an angle nearly to the repose angle at top of the bed, and Nouch et al.\(^\text{21}\) also report the similar feature. These results are supposed to indicate that the lower surface is dominated by particle properties. However, on the other hand, the results of DEM simulation by Nouch et al.\(^\text{16}\) show that the lower surface of deadman has a slope only at periphery and has a good agreement to the dissection results of Mizushima No. 4 blast furnace, then their results is almost similar to the results of this work. As one of the reasons for the differences among above works, a scale effect can be pointed out. That is, the cold model experiments are performed on a less than 1/10 scale of an actual hearth, while the simulations were performed on a full scale. Therefore, only the feature of deadman surface shape at periphery was mainly observed in the cold model experiments.

5.2. Simulation of the Erosion Profile of Hearth Refractory

Assuming that the observed erosion profile shown in Fig. 8 was formed in the period when the maximum heat load was observed, simulation for the erosion profile of hearth refractory was made based on the estimation of inner furnace state in the period, and correspondence to the observed result was examined. Table 6 shows the operational condition. The procedure to obtain the inner furnace state such as the bulk density distribution and the lower boundary of deadman was the same as the above estimation. The results are shown in Table 7 and Fig. 18.

Figure 19 and Table 8 show the layout and property of the hearth refractory. As for the properties of the inner hearth materials, such as heat conductivity and density, the observed values of this work were used. Though, the particle size and void ratio of deadman were assumed to be 20 mm and 0.4, respectively, since the permeability of the deadman is supposed to be good in the target period. The simulation was made by use of the mathematical model developed by Takatani et al.\(^\text{22}\) The erosion profile was successively updated in the reiterative calculation process where temperature distribution evaluation by flow and heat transfer analysis of the hearth and removal of refractory pieces based on erosion criteria shown in Table 8 were made, and finally, the “thermo-equilibrium” erosion profile was obtained when no removal process of refractory was required.

The result is shown in Fig. 20. Comparing the observed profile, which is also drawn in the figure, a good agreement can be found, and therefore, the estimation procedure and

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**Table 6.** Operational conditions (’98.8/22–9/10).

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>3510 t/d</td>
</tr>
<tr>
<td>Blast volume</td>
<td>2544 Nm³/min</td>
</tr>
<tr>
<td>Blast pressure</td>
<td>277 kPa</td>
</tr>
<tr>
<td>Top gas pressure</td>
<td>175 kPa</td>
</tr>
<tr>
<td>Coke rate</td>
<td>377 kg/THM</td>
</tr>
<tr>
<td>PC rate</td>
<td>120 kg/THM</td>
</tr>
<tr>
<td>Ore to Coke ratio</td>
<td>4.33</td>
</tr>
</tbody>
</table>

**Table 7.** Bulk densities of packed bed in the furnace.

<table>
<thead>
<tr>
<th></th>
<th>Coke layer</th>
<th>Ore layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp zone</td>
<td>520</td>
<td>1819</td>
</tr>
<tr>
<td>Cohesive zone</td>
<td>546</td>
<td>2262</td>
</tr>
<tr>
<td>Dropping zone</td>
<td>647</td>
<td>–</td>
</tr>
</tbody>
</table>

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Fig. 17. Stress field and deadman shape in the hearth.

Fig. 18. Stress field and deadman shape.
5.3. Simulation of the Hearth Condition at Blow-out

By use of numerical analysis, the heat load and solidified layer at blow-out were simulated and compared with the observation. Table 9 shows the operational conditions in the period of blow-out. The shape and position of the deadman was set according to the results of core-boring, and particle size in the deadman was assumed to be 1 mm as a representative value. As for void ratio of deadman, since no certain values were obtained from the samples, 0.4, which corresponds to ordinary value of coke bed, was assumed. And, according to the dissection results that iron was supposed to be solidified at center, for upper boundary condition, inlet of molten iron was localized at periphery, and boundary temperature at the center was set to the solidified temperature, 1323 K.

Figure 21 shows the simulation result. In the figure, no molten iron flow can be found, while the solidified region distributes in most of the hearth. This situation coincides with the image predicted by the observed Mn distribution. Therefore the deadman with fine coke obstructs the molten iron flow, and can be regarded as a “less permeability layer”. On the other hand, the evaluated hearth bottom temperature denoted in the figure is very low and corresponds to the observed level.

However, especially for the upper part of the hearth condition, an agreement between the simulation results and the observation ones are not sufficient. Therefore, in case of the widely formation of solidified layer, the simulation area has to be extended upward in the furnace.

6. Conclusion

A dissection investigation was made in Kokura No. 2 blast furnace after blow-out. Through the analysis of boring samples, the following knowledge about the hearth condition was obtained. That is, (1) the deadman was floating in the metallic iron pool of the hearth. (2) The coke particles in the deadman were considerably fine. (3) The “effective” flow region of molten iron was extremely small and located around the tap hole level. And according to simulation results, (4) the estimation method of the lower boundary surface of deadman based on the rigid plastic theory is found to be practical and valid. Then, (5) the erosion profile estimation by use of the property data of hearth materials obtained in this work has a good agreement to the observation. And finally, (6) by use of the numerical simulation, it is confirmed that the observed deadman which consisted of fine coke can be regarded as “less permeability layer”.

However, there are several phenomena or questions still remaining to be cleared up, such as formation and annihilation process of “less permeability layer”, which are related to a changing mechanism of the heat load of hearth, and mechanism inducing “elephant foot” shaped erosion of hearth. Many new investigations and further researches are expected in the future.
Nomenclature
\( \rho \): Bulk density [kg/m\(^3\) · bed]
\( \sigma \): Stress tensor [Pa]
\( v \): Displacement velocity [m/s]
\( R_w \): Source term [kg/m\(^3\)/s]
\( f \): External force [N/m\(^3\)]
\( Y \): Yield strength [Pa]
\( \varepsilon \): Strain rate tensor [1/s]
\( s_{ij} \): Deviative stress [Pa]
\( \dot{\varepsilon} \): Deviative strain rate [1/s]

REFERENCES
12) K. Kondo, Y. Oono and Saito: Tetsu-to-Hagané, 72 (1986), S82.