1. Introduction

The life of a blast furnace is determined mainly by the erosion of refractories. In the past, damage to shaft refractories was a rate-controlling factor of furnace life in many blast furnaces. However, owing to progress in cooling techniques and techniques for repairs during operation, recent years have seen many cases where the erosion of hearth refractories governs furnace life. For the erosion of hearth refractories, dissection investigations of many blown-out blast furnaces were carried out in the past and erosion profiles and the deterioration condition of refractories were investigated. A schematic representation of the erosion of hearth refractories is shown in Fig. 1. It has been reported that a certain region of refractories is eroded and lost, that molten iron penetrates the innermost side of the remaining part, and that there is a brittle layer behind this molten iron-penetrated region. For the mechanism of the erosion of refractories, it is estimated that as shown in Fig. 2, when molten iron penetrates the pores of refractories and the carbon of refractories is dissolved, fine cracks are formed behind the molten iron-penetrated region and embrittlement proceeds, resulting in disintegration. For the erosion profiles of the furnace bottom, bowl type erosion and mushroom type are typical erosion profiles. In the former, refractories in the middle portion of the hearth bottom are eroded to a maximum degree, and in the latter, refractories at the furnace bottom corners are eroded. In particular, the mushroom type erosion has posed a problem. On the basis of the knowledge obtained from studies on molten iron flow that the mushroom type erosion is promoted by the concentration of molten iron in coke-free regions formed at the furnace bottom corners, many recent blast furnaces are designed in such a manner that the entire furnace bottom is made as a coke-free region by increasing...
the depth of the hearth of the furnace bottom in order to lessen the concentration of molten iron flows at the corner.

However, in a blast furnace having a deep bottom, molten iron flow through the whole furnace bottom increases although molten iron flow at the corner is lessened, with the result that the sidewall portion intermediate between tapping holes and furnace-bottom corner is locally eroded. This is what is called “Otafuku” (mumps face) type erosion. In recent years, cases where this type of erosion occurs have become numerous. Figure 3 shows an example of this type erosion.

The Tobata No. 1 BF was blown in in December 1985 and blown out in January 1998 after 12 years and 2 months of operation. In the latter period of operation, the temperature distribution of the hearth sidewall showed “Otafuku” type erosion and this erosion determined the life of the blast furnace. Because this blast furnace was not relined and operation was shifted to the No. 4 BF on the day after the blowing out, the blast furnace was blown out in a packed condition and not in an empty condition. For this reason, although a dissection investigation could not be carried out, core boring of hearth sidewall was carried out after thorough cooling of the furnace body, part of the bricks and salamander were sampled and the condition of erosion and the properties of the salamander were investigated.

On the basis of the results of these investigations, changes in the sidewall temperature during operation were considered and the mechanism of erosion of the sidewall by the molten iron flow in the hearth and the actual condition of viscous layers that protect the sidewall were estimated.

2. Properties of Hearth Refractories

Table 1 shows the properties of the main carbon blocks used in hearths from the 1970s onwards.\cite{13,17} Refractories of Types A and B were mainly used in blast furnaces blown in in the 1970s. However, bricks having fine pores capable of suppressing the penetration of molten iron into the pores were later developed and in blast furnaces blown in in the latter half of the 1980s, carbon blocks of Type C to which Si and Si–C are added and which have an average pore diameter of not more than 1 \mu m were used and carbon blocks of this type were also used in the Tobata No. 1 BF. For hearth refractories, Type D in which pores are further refined and Type E having high thermal conductivity to increase cooling capacity were developed. These hearth carbon blocks are used in blast furnaces blown in from the latter half of the 1980s onwards. And these types are used in many blast furnaces in operation at present.

Many of the dissection investigations carried out in the past were for blast furnaces using mainly Type A or B refractories having large average pore diameters, whereas in Tobata No. 1 BF are used Type C refractories which were developed to prevent the penetration of molten iron. For this reason, one of the purposes of the investigation conducted this time was to ascertain whether the expected improvement in material property was obtained and whether there was a change in the erosion mechanism due to a difference in material property.

3. Method of Investigation

Sampling positions for core boring are shown in Table 2 and Fig. 4. For example, 9A-25 indicates the location under the No. 25 tuyere at Level 9.

The sidewall temperature during operation was measured in the positions 50 and 150 mm from the back face of a block and the remaining thickness of the block was estimat-
ed from the transition of the sidewall temperature. Three locations were selected from Level 9 at which it was estimated that erosion had proceeded most in the height direction. That is, the No. 25 tuyere under the No. 3 taphole for which the remaining block thickness is estimated to be minimum in the circumferential direction, the adjacent No. 24 tuyere, and the area under the No. 8 tuyere which is intermediate between the Nos. 1 and 2 tapholes at the same level and for which the remaining block thickness is estimated to be relatively small. Moreover, one location under the No. 33 tuyere from lower Level 7 was selected. In this area, the sidewall temperature reached a maximum value in a period closest to the day of blowing out, that is, the days elapsed from the last brick erosion to the day of blowing out are estimated to be a minimum. Table 2 also shows the date on which the thermometers embedded in each selected location recorded a maximum value. For 9A-25, there was an obstacle behind the planned sampling location (thermocouple-embedded place) and in actuality, samples were taken from a place about 1 m nearer to the No. 24 tuyere.

Core boring was carried out by making bores horizontally from the outside of the shell toward the center using a drill 200 mm in diameter. When the drill reached the salamander and could not advance anymore, it was replaced by a drill 100 mm in diameter. In this manner the residue in the hearth was bored and sampled. Figure 5 shows an example of a core after sampling. Because part of the block on the hot face side where disintegration had proceeded was dislodged by impacts during core boring, the positions of the taken sample and the dislodged portion were determined by observing the bore side along with the sample and measuring the distance.

For core samples thus taken, the appearance and the properties of cut sections were observed. The core was divided into a metal-penetrated layer, a weakened or an embrittled layer, a sound layer which a small amount of metal penetrated, and a weakened layer in which the block has become brittle although metal did not penetrate. The samples were taken with each layer separated. However, no crack was observed on the bore side in the furnace (Fig. 5) and it was estimated that the layers had been separated by impacts during sampling.

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The appearance of the core sample 9A-25, which is close to the most eroded portion, is shown in Fig. 8 and the relationship between the core sample and the core is shown in Fig. 9. In the core sample 9A-25, which had a remaining block thickness of about 800 mm, the portion near a 600 mm thickness showed severe embrittlement. The sample was separated in this position and part of the sample was disintegrated and lost to such an extent that the separated sections did not mate with each other. In addition, also on the core side, cracks were observed from the cold surface of

Table 2. Core-boring location of T1BF

<table>
<thead>
<tr>
<th>Location level/tuyere</th>
<th>Location taphole</th>
<th>Date of max temp.</th>
<th>Thickness meas (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9A-25</td>
<td>under 5TH</td>
<td>1996/04/08</td>
<td>595</td>
</tr>
<tr>
<td>9A-24</td>
<td>under 5TH</td>
<td>1995/01/27</td>
<td>780</td>
</tr>
<tr>
<td>9A-8</td>
<td>1-2TH</td>
<td>1994/03/17</td>
<td>936</td>
</tr>
<tr>
<td>7A-33</td>
<td>4-1TH</td>
<td>1997/11/17</td>
<td>950</td>
</tr>
</tbody>
</table>

Fig. 4. Core-boring location of Tobata 1BF

Fig. 5. Inside of 9A-8 core.
the block to near the 600 mm thickness portion along the full circumference and it is estimated that large cracks were formed in the block during operation. Figure 8 shows sections obtained by cutting the innermost portion, which had been obtained by the drill of 100 mm in diameter, in two directions. These sections show lustrous surfaces and hence they are considered to be substantially composed of a metal structure.

The appearance of the core sample 7A-33, which is considered to have been eroded most recently, is shown in Fig. 10 and the relationship between the core sample and the core is shown in Fig. 11. In this core sample, the portion capable of being taken by the drill of 200 mm in diameter was about 920 mm long and almost all this portion was a sound layer. Figure 10 also shows sections obtained by cutting the innermost portion, which had been obtained by the drill of 100 mm in diameter, in two directions. Although a small amount of metal penetrated, the texture of the block remained. Between the portion of the core sample obtained by the drill of 200 mm in diameter and that obtained by the
drill of 100 mm in diameter, there is a region where the sample was lost in places, and minute pieces considered to be part of the brittle layer were recovered.

These views about the results of the observation are compared with the results of dissection investigations carried out in the past. The views about the core sample 9A-8 are similar to those of the past dissection results. Therefore, although the pores in these blocks were finer than in conventional blocks (Table 2), the blocks did not escape from being penetrated by molten iron and the estimated mechanism is the same as in conventional blocks, i.e., penetration of molten iron → formation of an embrittled layer on the shell side of the molten iron-penetrated region → growth of the embrittled layer → erosion. However, compared with many blast furnaces blow in in the 1970s, the amount of remaining refractories is large and the thickness of the embrittled layer is small in spite of the long campaign life. Furthermore, in a conventional blast furnace, the penetration of molten iron and the growth of an embrittled layer were observed even after 1.5 years of operation after blowing-in, whereas in the core sample 7A-33 after 1 year and 2 months after the last erosion, the embrittled layer was very small as described above. Therefore, this demonstrates that the improvement in the resistance against the penetration of molten iron results in a decrease in the average erosion rate, contributing to the extension of life.
4.2. Results of Measurement of Physical Properties of Each Layer

Figure 12 shows the results of density measurement for each portion of each of the samples taken. The abscissa indicates the distance from the cold surface of the carbon block. The point of the minus coordinate on the leftmost side indicates a stamping material. The rightmost side indicates the zone in which each core sample was taken using the drill of 100 mm in diameter. The core samples 9A-24 and 9A-25 have a density of 6 to 7×10³ kg/m³ and hence the composition of these core samples is substantially metallic iron. The density of the core sample 9A-8 is about 5×10³ kg/m³ and hence this shows that other components are also present although this core sample is mainly composed of metal. In contrast to these core samples, the density of the core sample 7A-33 is about 2×10³ kg/m³ and this backs up the result of the observation that almost all components of the core sample are the block itself. The second point from the right-hand end shows that only the core sample 9A-8 has a density of about 3.5×10³ kg/m³ and this is in agreement with the result of the observation that a large amount of metal penetrated, replacing part of the block. The density of other core samples is about 2×10³ kg/m³ and this is in agreement with the result of the observation that the texture of the block is sufficiently maintained although a small amount of metal is observed here and there. The results of measurement of the porosity, strength and thermal conductivity for each position of the core samples are shown in Figs. 13, 14 and 15, respectively. For the portion of the brittle layer, some of the core samples for measurement could not be prepared. In the portion of the sound layer, porosity decreased from initial values, strength increased from initial values, and thermal conductivity showed high values. Also on the hot face side, thermal conductivity showed high values. For these high values of thermal conductivity, the penetration of metallic iron is considered to be the cause. And on the sound layer side, this suggests that the texture became dense, but the cause is unknown. Next, Fig. 16 shows the chemical component concentrations of the extraneous substances of the core sample 9A-8 in which the textures of the metal-penetrated layer, brittle layer and sound layer were clear. On the abscissa, the hot block face excluding the metal-rich layer provides the standard. And the three left-hand points indicate a layer in which a large amount of metal penetrated, a layer in which a small amount of metal penetrated, and a brittle layer in this order, and the area on the right-hand portion from the fourth point indicates a sound layer. In (a) are shown the concentrations of alkalis and zinc and in (b) are shown the concentrations of iron and SiC. The accumulation of alkalis and zinc in embrittled portions of bricks have been reported in many investigations. In comparison with these reports, the results of the present investigation have the following features. (1) The concentrations of K₂O and ZnO were much lower than those of many past investigations. 6,8,11)}
Alkalis, along with NaO and K₂O, without a large peak were widely distributed from the hot face side to the cold face side. (3) The concentration of zinc showed a sharp peak in the portion of the embrittled layer. It is estimated that this accumulation of zinc had an effect on the progress of embrittlement.

5. Estimation of Properties and Formation Process of Metal-rich Layer Adjacent to Block

The structure of the residue in the hearth (metal-rich layer) of samples 9A-8 and 9A-25 was investigated in detail. Figure 17 shows the samples polished after embedding in resin. Sample 9A-8 shows a structure in which carbon or slag is included in metal. In a close observation, gold-red inclusions were observed at the boundaries where carbon or slag is included in metal. In sample 9A-25, the whole surface is metal and no carbon or slag inclusion is observed. The graphite size can be divided into four layers of a fine layer, a coarse layer, a fine layer and a somewhat coarse layer from the block side to inside the furnace. However, clear boundaries cannot be identified. Figure 18 shows the result of microscopic observation of the portion of 9A-8 where the gold-red inclusions were observed. The matrix structure is ferrite and graphite considered to have crystallized during the eutectic reaction is present. This suggests that solidification proceeded very slowly. In the sample, semitransparent gold-red TiN crystals were observed. Although TiN crystals are observed also in the matrix, they occur in large amounts at the boundaries between graphite and the iron base. The crystals in the matrix have polygonal shapes in which each side is in almost linear form, while those at the boundaries between graphite and the iron base have such shapes that the iron base side is in polygonal form and the graphite side is in serrated form. Although the metal-rich layer of 9A-8 and sample 9A-25 are composed of graphite and ferrite, the precipitation of pearlite to a small extent is also observed. This pearlite held the lamellar structure without granulation. For graphite, eutectic graphite has sizes observed in usual pig iron, whereas proeutectic graphite is gigantic. Table 3 shows the chemical compositions of samples taken from 9A-8, in particular, [1] the portion where carbon is included and [2] the metal portion without inclusions and 9A-25, in particular, [1] the portion of large graphite size and [2] the portion of small graphite size. In all the samples, the carbon concentrations are considerably higher than saturated molten iron. The high carbon concentrations may be ascribed to some carbon source, which solidified together with molten iron, or a repetition of precipitation and accumulation of carbon with the graphite structure serving as a nucleus. As carbon sources, coke, block carbon, and Kish graphite, which is formed by the precipitation of carbon dissolved in molten iron are conceivable. However, it is difficult to identify them. A comparison of 9A-8 and 9A-25 reveals that the Si and S concentrations are higher in 9A-8. The thermal conductivity measured by the laser method is shown in Fig. 19. The thermal conductivity of steels having different carbon contents is also shown for comparison. The thermal conductivity of the samples 9A-8 and 9A-25 was 35 to 45 W/m/K at room temperature and 15 to 20 W/m/K at 800°C.

From these results, it is estimated that the metal-rich layer adjacent to the block was formed as follows. [1] Molten iron adhered to the block surface and a layer having a thickness with which the inner surface of the furnace reaches a eutectic temperature was formed. In 9A-8 whose remaining brick thickness is larger than that of 9A-25, the
cooling of the hot face was weak, a solidified layer was not formed in a stable manner, a pasty layer during eutectic reaction was thick, and hence an added Ti source could be taken in. [2] While the temperature of the solidified layer was changing near the eutectic temperature due to a temperature change in the furnace, carbon was supplied from the molten iron in the furnace. This carbon was diffused toward proeutectic graphite and precipitated, resulting in an increased thickness. As a result, proeutectic graphite grew and a layer of high carbon concentration was formed. [3] After the blowing-out of the blast furnace, the solidified layer was very slowly cooled and the carbon in austenite precipitated by graphitization directly in the existing graphite and became ferrite. Partially, however, segregation of carbide stabilizing elements occurred and austenite present far away from the existing graphite reached a eutectic transformation temperature and became pearlite. The ferrite of the matrix structure and the small amount of lamellar pearlite were thus formed.

In view of the results of the observation, the role of titanium compounds and the mechanism of sidewall protection are considered. Although it has been reported that titanium compounds are present in the hearth bottoms of blown-out blast furnaces, in many cases they are Ti(C, N) which are concentrated in layers of lumps in the corners of a hearth bottom. [2,18,19] The part which was investigated by the core boring this time is the sidewall part which is intermediate between the corner portion and the taphole and the amount of TiN, which is present in part of the samples, was very small. In corner portions which wear greatly by erosion in the mushroom type erosion, the protection mechanism that molten iron contact is prevented by the covering of the brick surfaces by titanium bears can be expected. In contrast, in the “Otafuku” type erosion, it is difficult to expect the protection mechanism that titanium bears cover the brick surfaces in the side wall under the taphole where wear is great and in this case it might be thought that titanium which is present in concentrations higher than a certain level as a molten iron component and impedes the fluidity of molten iron near the sidewall by partially mixing in solid crystals. [20] It is a solidified layer of high carbon concentration formed by the mechanism estimated above that contributes to the protection of carbon blocks and it might be thought that the presence of this layer as a buffer between molten iron and the carbon blocks prevents the dissolution of carbon of the carbon blocks even when molten iron with unsaturated carbon comes.

6. Considerations of Effect of Blast-furnace Operation and Flow of Molten Iron in Hearth on Sidewall Erosion

The degradation status of blocks and the properties of the residue in the hearth near the blocks were considered above. These phenomena may be the results of the effect of molten iron during blast-furnace operation. Therefore, the operating conditions in the campaigns of Tobata No. 1 BF were investigated and the effects of molten iron flow on the erosion of blocks were considered. Figure 20 shows the transition of operation since the blowing-in and changes in the minimum value of estimated remaining brick thickness.

The estimated remaining brick thickness was indicated at a 1150°C position determined from temperatures of the brick-embedded thermometers by heat transfer calculation. In the core boring places after the blowing-out, remaining brick thickness values estimated by this method were almost in agreement with measured values of remaining thickness.

From 1985 when the Tobata No. 1 BF was blown in to the end of 1988, two-BF operation was carried out at Yawata Works. Productivity was low and variations in iron output and fuel rate were great during this period of production curtailment due to economic recession. Within two years after the blowing-in, great erosion of about 1 m maximum occurred and a calculated viscous layer thickness increased or decreased greatly. In view of this, it is thought that variations in the brick temperature were great, accelerating the fatigue and degradation of materials, which might have provided a cause of the later brick erosion. After that, one-BF operation was carried out following the blowing-out of the Tobata No. 4 BF and in 1990–1993 operation was continued with an annual iron output of about 9 500 t/d (productivity ratio of about 2.2 t/d/m³). There were few shutdowns and the furnace condition was such that sidewall viscous layers grew little. In this period, the erosion of the most eroded portion did not proceed much, while the erosion of other portions proceeded. Also after 1993, stable operation with a high iron output was aimed at. However, the estimated residual brick thickness became not more than 1 000 mm in a broad range, the sidewalk and hearth temperatures periodically repeated rise and fall, the erosion of sidewalk bricks also proceeded.

As an example of this situation, Fig. 21 shows a hearth sidewall temperature rise that occurred from the end of 1996 to the beginning of 1997. This figure shows sidewall temperature changes at Levels 8, 9 and 11. The temperatures of 9A-25, 8A-26 and 11A-26 rose and fell in the same period, while in other parts in the circumferential direction there was no great temperature change. It is estimated therefore that there were strong flows of molten iron that moved from under the No. 3 taphole upward. Furthermore, at Level 8 a similar tendency of temperature change, though somewhat low, is observed also in 8A-21. It is estimated
that as shown in Fig. 23(a), upward flows in a somewhat wide range at lower level were integrated into strong narrow flows as they approached a taphole. By focusing attention to the packing structure of a hearth portion by carrying out model experiments and using a mathematical model, the authors have been conducting an investigation of molten iron flow. And they have reported that in comparison with a case where the whole hearth is a coke-packed bed, when the deadman floats and a coke-free zone is formed, the molten iron flow velocity under the taphole increases and the temperature rises. In the above-described Tobata No. 1 BF, the phenomenon that the temperature in the center of the furnace bottom drops and the sidewall temperature rises was frequently observed. Therefore, it is concluded that periodically occurred the phenomenon that in the center of the deadman a region of low liquid permeability is formed to the furnace bottom, while in the peripheral part of the furnace bottom the deadman coke floats, forming a coke-free zone.

Figure 22 shows a temperature distribution in the circumferential direction of Level 9 in a different period. As described above, in the period from the end of 1996 to the beginning of 1997, only the temperature of the area under the No. 3 taphole (near the No. 25 tuyere) rose and the area under the No. 3 taphole eroded most. Therefore, the use of the No. 3 taphole was stopped and No. 1, No. 2 and No. 4 tapholes were used. In the summer of 1997, the temperatures of the area under the No. 4 and No. 1 tapholes (Nos. 31–34 tuyeres) and of the area under the No. 2 taphole (near the No. 17 tuyere) rose. In this blast furnace, there was no case where the temperature in the whole circumferential direction rose in the same period. The mechanism of temperature rise under the No. 2 taphole is the same (Fig. 23(a)) as the case of the temperature rise under the No. 3 taphole, which was described above. However, it is estimated that the mechanism of temperature rise in the area under the No. 4 and No. 1 tapholes is, as shown in Fig. 23(b), such that when either of the two tapholes was used, the temperature rose in the middle portion, which is the passing point of flows of molten iron advancing to the taphole. This also supports that flows of molten iron advancing to the taphole cause the sidewall erosion.

On the basis of the foregoing, the erosion and protection mechanism of the hearth sidewall will be discussed below.
In the hearth sidewall portion, as described in 5 above, a viscous layer of low flowability that contains Ti or a solidified layer of high carbon concentration is formed between a molten iron flow and the carbon of brick, preventing erosion. However, depending on changes in the packing structure, for example, when the liquid permeability in the furnace center is worsened due to the formation of a coke-free region in the peripheral portion of the deadman, a strong molten iron flow is formed in the sidewall portion and, particularly, under a taphole, shrinks the viscous layer and the solidified layer. Because usually multiple tapholes are used by making a selection among them, during the use of a remote taphole the flow velocity of molten iron decreases and the viscous layer and solidified layer grow. However, if the shrinkage rate of the viscous layer and solidified layer during the use of a taphole is higher than the growth rate of these layers during non-use, these layers shrink on average. When the thickness of these layers becomes zero, the bricks near these layers erode. Therefore, the positional relationship and frequency of use of multiple tapholes are also related to the erosion of bricks. Furthermore, the degree of saturation of carbon in a flow of molten iron has also a great effect on the dissolution of a solidified layer of high carbon concentration and the erosion of bricks, and it is concluded that variations in operation have an effect on the erosion of bricks because they provide conditions under which molten iron of unsaturated carbon is apt to be produced.

7. Conclusions

After the blowing-out of the Tobata No. 1 BF, the sidewall core boring of the blast furnace was carried out. Bricks and residue in the hearth were sampled and investigated in order to estimate the erosion and protection mechanism of the hearth sidewall.

(1) It was estimated that the erosion of hearth sidewall bricks occurs by the two mechanisms: [1] due to the penetration of molten iron into the bricks and the dissolution of bricks into molten iron, the carbon of bricks is gradually replaced by molten iron and is lost; and [2] an brittle layer is formed on the shell side rather than in a molten iron-penetrated region, and expands due to thermal stress and penetration of zinc, etc., resulting in exfoliation. Although no great change in the mechanism was not observed compared with the past dissection investigations, the amount of penetrating molten iron was reduced and the growth of the embrittled layer was suppressed as the effects of the brick pore diameters reduced from those of conventional bricks.

(2) As a result of investigation of the residue in the hearth near sidewall bricks, [1] it became apparent that the residue in the hearth is a layer mainly composed of iron having a density of 5 to 7 t/m³ and [C]>10% and high thermal conductivity. Although lamellar pearlite exists partly in the solidification structure, the greater part of the matrix is ferrite. It was estimated that the solidification structure is molten iron which solidified gradually while entraining carbon sources. [2] Slight amounts of TiN crystals were observed in part of the samples by microscopic observation.

(3) Examples of blast-furnace operation and rise in the hearth sidewall temperature were investigated. It was estimated that flows of molten iron strengthened by the flotation of the deadman which move in the hearth toward tapholes due to the packed condition of the deadman are the cause of the sidewall temperature rise and that the use condition of tapholes has a great effect on the sidewall temperature rise. A mechanism of sidewall erosion by the shrinkage of a viscous layer and a solidified layer near the bricks was estimated.

REFERENCES