Analysis of the Deadman Features in Hearth Based on Blast Furnace Dissection by Comprehensive Image-processing Technique

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Information of the coke packing condition and its size distribution in the deadman is critical for understanding the blast furnace hearth phenomenon. In this study, a commercial blast furnace was frozen and dissected. It was found that the upper part of the deadman below the taphole was mainly filled with coke and slag. In the area from the height of about 912 mm below the taphole and downward, the hearth was mostly consisted of coke and hot metal and the depth was about 2 320 mm. The bottom part of the hearth with a height of 214 mm was coke free and filled only by hot metal. A multi-feature analysis method based on comprehensive image-processing technique was used for measuring the size of the coke and the voidage of the deadman. It was found that the mean sizes of coke in the upper and lower parts of deadman were 34.39 mm and 32.12 mm respectively. The overall mean size of coke was 33.3 mm. The size of the coke in the deadman was reduced by 36% comparing with its original size. At the edge of the deadman, the voidage increased rapidly from 10.7% to 41.1% at the depth of 1.0 m to 2.2 m below the taphole centerline. In the centre of the deadman, the voidage increased slowly from 16.6% to 31.3% and then decreased. The average voidage of the edge and the centre areas were 38% and 25% respectively.

KEY WORDS: blast furnace; deadman; coke; voidage; digital image processing.

1. Introduction

A large area of coke called ‘deadman’ is formed in the low part of ironmaking blast furnace. The recognition of the deadman is significant to the evaluation of the performance for blast furnace.1) In recent years, with the increase of smelting intensity, the molten iron flow brings much more heat into the hearth, and therefore the hearth refractory is exposed to high temperature iron and is eroded through thermo-chemical solution such as carbon dissolution into molten iron. This process of the dissolution of C in hot metal is supposed to be affected by the inner hearth state, especially the permeability of deadman.2–4) As a result, the deadman zone plays a crucial role in modern high productivity blast furnaces. The permeability of the deadman is directly related to the coke size distribution and deadman voidage. Therefore, effective evaluation of the coke size and voidage of the deadman is critical for understanding the blast furnace hearth performance and the process optimization.

The properties of the deadman are extremely difficult to estimate. In order to understand the deadman state of an operating blast furnaces, researchers have made numerous efforts to observe, characterize, and/or measure blast furnace phenomena by inserting probes at different locations in the blast furnace.5) Most of these measurements are limited from the top to the cohesive zone, and for the bottom to the raceways. Very limited direct measurements have been attempted in the hearth zone of blast furnace. Core drilling at the tuyere level was used for sampling the coke in some studies.6–11) Properties of the sampled tuyere coke was measured and correlated to the degradation of the coke in BF. The tuyere coke samples were screened to determine the particle size distribution. Those tests adopted particle coke method to measure the carbon consumption rate. But the technique can only be used at stoppages. It is fairly expensive and laborious to analyze the samples. Furthermore, the coke size of the deadman at the tuyere level (behind some of the raceways) is not necessary to reflect the conditions of the deadman in the lower part of the furnace hearth.

In addition to the experimental investigations mentioned above, numerical simulations have been made on the molten iron flow and liquid permeability of deadman in hearth at given inner hearth condition.12–15) Nouchi et al.16) simulated the stress field, solid flow and the coke free space shape by using the discrete element method (DEM). The replacing mechanism of the deadman, the flow pattern and the less...
permeability layer formation were discussed. It is no wonder that these efforts are being supplemented with limited laboratory experimental investigations simulating specific aspects of the furnace in isolation. Though, the experimental data are so scarce that some simulation work only simulate individual processes. Thus, 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.

The real inner hearth condition of a commercial furnace can only be observed through the dissection of furnace after blow-out. In the dissection investigations of blast furnaces carried out in the ’80s and ’90s, features of the hearth erosion were found to be various, such as “bowl-shape” and “elephant foot shape” erosions. Due to the various coke morphology and the complexity of the deadman state in this high temperature heterogeneous zone, the knowledge on the inner hearth deadman is very limited. It is difficult to acquire the state of the coke in the deadman.

In this study, a large commercial blast furnace was frozen after blow-out without a salamander tapping. The BF was put into operation in September, 1994 and shut down in September 2013 for maintenance. The BF has been operated smoothly at a productivity of about 2.27 tHM/(m$^3$·d) and the average blast temperature was 1 513 K (1 240°C). The profile of the furnace hearth was mostly consisted of coke and hot metal and the height of about 912 mm below the taphole centerline, the wear of the bricks are serious.

3. Results and Discussion

3.1. Overview of the Hearth Profile and Deadman State

The dissected furnace hearth was kept to the original shape and state as completely as possible. The hearth was cut into many pieces, as shown in Fig. 2.

2.2. Analysis Method

The coke size in the deadman can be analyzed by digital image processing technique, which is a low cost and quick method. Photoshop is one of the digital image processing software developed to compute the size of coke in the deadman from digital images. Grayscale digital images of the samples were first acquired manually from digital camera, individual frame capture from video or through scanned (digitized) photographs. The image of the sample was processed and analyzed in Photoshop in following four steps. The first step is to determine the scale of each image taken in the field. The second step performs the automatic delineation of the components in each of the images that are processed to the binary image. The third step involves the calculation of the size based on the pixels. Finally, the fourth step concerns the graphing and various outputs to display the size results.

2. Overview of the Blast Furnace Hearth

A commercial blast furnace at Baosteel with inner volume of 4 350 m$^3$ was dissected in this study by using rope saw after blow-out without a salamander tapping. The BF was put into operation in September, 1994 and shut down in September 2013 for maintenance. The BF has been operated smoothly at a productivity of about 2.27 tHM/(m$^3$·d) and the average coke and coal consumption rates were maintained as 315 kg/tHM and 180 kg/tHM, respectively. The average blast temperature was 1 513 K (1 240°C). The profile of the furnace hearth with nominal diameter of 14 m is shown in Fig. 1. The furnace has 4 tap holes, which were tilted up for 10 degree to extend its campaign life. Four cooling staves were installed below the tap holes level. The depth of the salamander is 3.4 m, which is 24.3% of the hearth diameter. UCAR carbon brick with high thermal conductivity are mainly used at the hearth sidewall. The sidewall of the tap hole area is about 2.4 m thick, which consists of NMD bricks with 45–55 W/(m.K) of thermal conductivity near cooling staves and NMA bricks with 18–22 W/(m.K) of thermal conductivity near the hot surface. At the furnace bottom, two layers of integrated ceramic cup were built on top of the three layers of large carbon block.

The dissected furnace hearth was kept to the original shape and state as completely as possible. The hearth was cut into many pieces, as shown in Fig. 2.
depth was about 2320 mm. The coke free space region which sits on the top of the ceramic bottom was occupied by hot metal only with a depth of 214 mm. The upper part of the deadman below the taphole centerline, where the hot metal was hardly found, was mainly stuffed with coke and slag. In the normal blast furnace operation, the slag would sit above the taphole and there were only coke and hot metal below the taphole. The abnormal phenomenon was mainly caused by the floating deadman during the blow down process. The deadman floated which gave the space for the hot metal as well as slag sinking for the blast pressure reduced to zero. It can be inferred from observations that the deadman and the burden above can float on the liquid metal in hearth and can move down during tapping. The results was consistent with our previous research. The lower and upper parts of the deadman are shown in Figs. 4 and 5 respectively.

Image acquisition was critical in the analysis. In order to obtain high quality images which are representative of the entire deadman assemblage, sampling strategies must be carefully considered. The location of image taken was important, and there were two sampling methods, random and systematic. Systematic method has been used for this investigation. Another consideration was the angle of the surface been photographed. Ideally, the surface should be perpendicular to the camera lens. Images were taken randomly in the field and a rule was used to provide scale in the images. Some typical images taken in the field for measurement are shown in Fig. 6.
3.2. Coke Size in the Deadman

For a given micrograph, particular characteristics of gray level are present because different minerals make the intensity of the reflected light different. Image processing was based on the different reflectivity of the mineral according to which the gray distribution was used for distinguishing. It can have a good application to distinguish two kinds of minerals when the difference of reflectivity between them was large. After the image acquisition, the next step was to produce the binary images from the acquired digital images that showed the outlines of the particles visible in the image. The disposing process included contrast enhancement and background filtration. The main purpose of the disposing process was to increase the differentiation of different phases in the image, which was helpful for the preliminary identification of the image by gray feature. And then the minerals of coke can be selected by adjusting the tolerance processing. At last, the select area can be filled to be white, reversing the other area can be filled in black. As it can be observed from the Fig. 7, the binary image actually allows two color levels: white for cokes, black for hot metal.

After analyzing the mineral of the different compositions of deadman, the configuration of the morphology templates of the coke, slag and hot metal can be automatically recognized. Once the binary images have been completely edited, computation of size can be carried out. The most critical influence on the size calculation was the fines estimation. In every image there was a point below the resolution of the image where particles can no longer be “seen” and delineated. So the particles of coke were labeled manually. The resolution ratio of processing image is 72 pixel/inch (25.4 mm) and the number of the coke particle are counted by red point in Fig. 8. In the binary image, the pixels/unit of the image can be calculation, and the size of the figure can also be scaled by the measure of metre rule. So the size of the coke particle can be calculated by assuming the coke was in circle shape. The diameter of coke can be calculated by Eq. (1). Typical image taken in the field for calculation of coke size is shown in Fig. 8.

\[
d = \sqrt{\frac{4 \cdot L_A \cdot W_A \cdot S_C}{L_P \cdot W_P \cdot N}} \tag{1}
\]

where \(d\) is the coke diameter, \(L_A\), \(W_A\) and \(L_P\), \(W_P\) represent the length and width pixel of actual measurement and the acquired image. \(S_C\) is the total pixels of the coke and \(N\) is the number of the coke in the image.

The five most representative images of area 1 and area 2 were analyzed and mean size values were obtained. The obtained size and the original mean size of coke were given in Table 1. The mean size of coke in the upper and lower parts of the deadman were 34.39 mm and 32.12 mm respectively. The overall mean coke size in the deadman was 33.3 mm. The original coke size is about 52.14 mm. So the coke diameter in the deadman was reduced by 36%. The coke diameter in the lower part was reduced by 6.6% comparing with the coke in the upper part.

Furthermore, coke diameter in the upper parts of the deadman below the taphole centerline is 34.39 mm compared to original coke diameter 52.14 mm, coke consumption ratio is 71.3%. It was calculated as follows.

\[
\eta_{upper} = 1 - \frac{d(Coke)_{upper}}{d(Coke)_{original}} = 71.3\% \tag{2}
\]

When coke consumption is about 30% in solution loss reaction, carburization consumption ratio is 41.3% in upper deadman below the taphole centerline. Carburization consumption is mainly performed between the BF drop zone and taphole centerline. Coke consumption ratio in lower deadman can be calculated as Eq. (3).

\[
\eta_{lower} = 1 - \frac{d(Coke)_{lower}}{d(Coke)_{original}} = 76.6\% \tag{3}
\]
Carburization consumption ratio is 5.3% between the upper parts and lower parts of the deadman below the taphole centerline. Carburization consumption is a little. Coke of about 23.4% (100%−76.6%) are consumed by carburization or/and combustion in the raceway being forced by floating motion of the packed bed. Takahashi et al.\textsuperscript{23,24) simulated the renewal of coke in the deadman by drawing particles from the bottom-center of the cold model. They claimed that the coke in the deadman gets depleted due to carbon dissolution in the metal as well as being carried away during tapping; consequently it is replenished by the coke from above. As can be seen above, the deadman floated in the hearth. Thus, the coke in the deadman would come to the tuyere area for combustion with the packed bed floating and descending. Such as, in the storage state, the coke particles in the lower part of a hearth went upwards the raceway and were discharged. On the contrary, in the drainage state the packed particles below the raceway began to go downward from the furnace wall side. However, combustion in the raceway is capable in the storage state, but upper coke of the raceway may descend under the raceway while it changes from the storage state into tapping state. It is unknown whether coke under the raceway is the coke derived from lower deadman or not. Carburization reaction may occur during the moving to the raceway by floating motion. Because almost all melting iron drops near the end of raceway. So the quantitative consumption of coke in blast furnace needs to be further studied. And it can also be indicated that the major role of the coke charged from burden distribution in the centre area of the blast furnace was to support the material and ensure the liquid permeability. The other coke was combusted for providing the heat for operation.

### 3.3 Voidage of the Deadman

Combining the texture feature image with the gray feature image and formulating the corresponding rules and algorithm, the digital image processing was conducted by image processing so as to automatically analyze the percentage values of the coke, hot metal and slag in the deadman quantitatively. Area 3 and area 4 in Fig. 10 which represent the edge and centre region of the deadman were chosen for the voidage calculation. The voidage refers to the proportion of unoccupied volume (that is, iron or slag) in a volume of the total photo. 1.0 m depth from the taphole centerline was filled up with coke and slag, which represent the voidage of the deadman in the slag layer. Typical image taken in the field for calculation of deadman voidage was shown in Fig. 9.

The seven most representative images of area 3 and area 4 were analyzed and voidage of the deadman were obtained respectively. The obtained voidage were given in Fig. 10. At the edge of the deadman, the voidage increased sharply from 10.7% to 41.1% at the depth of 1.0 m to 2.2 m below the taphole centerline. Above 2.2 m, the voidage increases slowly. In the centre of the deadman, the voidage increased from 16.6% to 31.3% at the depth of 1.0 m to 2.6 m, and then decreased with further increasing depth to the 25.2% at the bottom of the furnace. The average voidage of the edge area and the centre area were 38% and 25% respectively. The voidage of the centre was larger than that of the edge in the upper deadman area especially the slag layer. At the edge in the hot metal layer, the voidage increases rapidly and is much higher than that of centre area. Velocity of molten iron flow near the side wall under a taphole were high. In contrast, the velocity in the packed bed was low. Temperature of the sidewall refractories corresponds well to the molten iron velocity and the molten iron velocity corresponds well to the heat transfer coefficient. With the increase of the convective heat transfer coefficient, hearth sidewall temperature increases, resulting in the increasing

| Table 1. Coke size characteristics in the deadman. |
| --- |
| Area | 1 | 2 | Original coke size |
| Total pixels | 138 252 | 144 996 |
| Coke pixels | 83 259 | 68 442 |
| Length and width of pixel | 2 248:984 | 2 248:1 031 |
| Length and width of actual, mm | 346:151.45 | 346:158.69 |
| Number of coke | 34 | 32 |
| Mean diameter, mm | 34.39 | 32.12 | 52.14 |

Fig. 9. Typical image taken in the field for calculation of deadman voidage. (Online version in color.)

Fig. 10. Voidage of the deadman at different depth in the hearth. (Online version in color.)
carbon unsaturation degree of the hot metal as well as the erosion and dissolution of the hearth sidewall. Thus, with the higher voidage and the lower velocity of the molten iron in the edge of the deadman near the sidewall, it is benefit for reducing the erosion of refractory materials, which was one reason for the long campaign.

4. Conclusions

The deadman in the high temperature heterogeneous zone are quite complex and possibly least understood in the context of the blast furnace. This article applied digital image-processing techniques to study the coke size and the voidage of the deadman in the BF hearth. Some conclusions can be drawn as follows.

(1) The blast furnace hearth was filled with coke. At the upper part of the deadman below the taphole centerline, the hot metal can hardly be found. It was mainly stuffed with coke and slag. At the height of 912 mm below the taphole centerline, the hearth was mostly consisted of coke and hot metal and the depth was about 2320 mm. On top of the ceramic, there is a coke free region with a height of about 214 mm which was occupied by hot metal only.

(2) The mean size of coke in the upper and the lower parts of the deadman were 34.39 mm and 32.12 mm respectively. The mean coke size of all the coke in the deadman was 33.3 mm. The original size of the charged coke is about 52.14 mm. The coke size in the deadman was reduced by 6.6% comparing with coke and slag. At the height of 912 mm below the taphole centerline, the hearth was mostly consisted of coke and hot metal and the depth was about 2320 mm. On top of the ceramic, there is a coke free region with a height of about 214 mm which was occupied by hot metal only.

(3) At the edge of the deadman, the voidage increased from 10.7% to 41.1% in the depth of 1.0 m to 2.2 m below the taphole centerline. With the depth continues to deepen, the voidage changed little. In the centre of the deadman, the voidage increased slowly from 16.6% to 31.3% and decreased as the depth over 2.6 m and the voidage is about 25.2% at the bottom centre area. The average voidage of the edge area and the centre area were 38% and 25% respectively.

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