Microstructure and Phase of Carbon Brick and Protective Layer of a 2 800 m³ Industrial Blast Furnace Hearth

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In this paper, the residual thickness of carbon brick, residual carbon brick and skull of a Chinese 2 800 m³ blast furnace hearth were studied in detail and the formation mechanism of skull and brittle layer were proposed. The results show that the remaining thickness of carbon brick is highly inhomogeneous in the height and circumferential direction. In the circumferential direction, the sidewall erosion in the range of 3.6 m under the taphole is more serious. In the height direction, the carbon brick at the distance of 1.0–2.0 m below the central line of the taphole is more obvious. The erosion of hearth bottom is “mumps face+ bowl” type erosion. The minerals of the hot surface of carbon brick used for more than nine years are mainly composed of KAlSiO₄, KAlSi₂O₆, Zn₂SiO₄ and ZnO as well as a small amount of ZnS, KCl and ZnAl₂O₄. Micro cracks resulted from the KAlSiO₄, KAlSi₂O₆, Zn₂SiO₄ and ZnAl₂O₄ are the inducement of formation of brittle layer. The main reason for the formation of macro cracks and brittle layer in carbon brick is the continuous accumulation of ZnO in micro cracks. The brittle layer mainly occurs in the region where the temperature of carbon brick is lower than 950°C. The skull above the central line of the taphole is mainly composed of Ca₂Al₂SiO₇, Ca₂MgSi₂O₇, CaTiO₃ and KAlSiO₄. The skull below the central line of the taphole is primarily comprised of Ca₂Al₂SiO₇, Ca₂MgSi₂O₇, CaS, Fe and Fe₃Si. The blast furnace slag phase in the skull below the central line of taphole is derived from the blast furnace slag that penetrates into the deadman coke. The blast furnace slag can be present below the central line of the taphole and adhere to the hot surface of the carbon brick to isolate the direct contact between the molten iron and carbon brick.

KEY WORDS: blast furnace; hearth erosion; damage investigation; carbon brick; brittle layer; potassium; zinc; skull.

1. Introduction

The campaign life of a blast furnace depends greatly on the erosion of hearth carbon brick.¹⁾ The performances of carbon brick in blast furnace hearth have been widely studied.^{1–12)} These studies indicated that the peripheral flow of molten iron, dissolution of molten iron, attack of zinc and alkalis, thermal stress and fluid induced shear stress are the reasons for the corrosion of carbon brick. With the deterioration of raw materials and fuels, the blast furnace is facing great challenges. Many of the challenges are connected to the high level alkalis and zinc constituents, such as increasing of coke reactivity and coke degradation, forming scaffolds on the inner walls of the furnace, the tuyere upward-warp and the erosion of lining, *etc.*^{1,3,4,12–21)} Previous researches on alkali metals and zinc in the blast furnace mainly focused on their enrichment and damage behavior to the raw materials and fuels,^{13–16,19,20)} but there is few studies on the carbon brick corrosion by alkalis and zinc at the

same time. Dissection studies of blast furnace hearth have proved the enrichment of K₂O and ZnO in the remaining carbon brick.^{1,21–23)} They suggested that K₂O and ZnO are the main reasons for the formation of brittle layer of the carbon brick. However, the phases and microstructure of the residual carbon brick were not investigated. Some researchers found that potassium permeating into carbon brick can lead to the formation of new phases such as nepheline (K₂O·Al₂O₃·2SiO₂) and leucite (K₂O·Al₂O₃·4SiO₂).^{2,4,12)} They claimed that the formation of new phases based on the reaction of K+SiO₂+3Al₂O₃·2SiO₂ is one of the important factors leading to carbon brick deterioration. Nevertheless, the main phases of minerals in micro porous and super-micro porous carbon brick are SiC, Al₂O₃ and a small amount of SiO₂ and 3Al₂O₃·2SiO₂.^{21,24,25)} The generation of new phases based on reaction of K+SiO₂+3Al₂O₃·2SiO₂ is not sufficient to account for the damage mechanism of carbon brick. Some researchers reported that the formation of brittle layer is caused mainly by thermal stress within the carbon brick.²⁶⁾ However, the brittle layer was also found in small carbon brick with high thermal conductivity.^{4,18,22,23)} The deterioration of carbon brick has also been evaluated in

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aggressive environments containing potassium vapors in the laboratory.^{2,4)} However, potassium, sodium and zinc coexist in the actual operations of blast furnace, and they affect the carbon brick simultaneously. Alkalies and zinc mineral deposits can attack the carbon brick and are important factors leading to deterioration. This may limit the service life-time of the hearth and lead to costly repairs. However, the evolution behavior of carbon brick in the environment with potassium, sodium and zinc existed simultaneously is not clear yet. With the increase of alkalies and zinc load in blast furnace, it is urgent to figure out the detailed influence of alkalies and zinc on carbon brick structure and performance in the industrial blast furnace to guide the blast furnace operation.

Due to the harsh environment, hearth lining will be eroded inevitably if they contact with the liquid iron and slag directly. Only by attaching a layer of solidified iron or slag on the carbon brick can the erosion be reduced and the campaign life of blast furnace hearth be prolonged. However, the information on the phase and the microstructure of skull extracted from the hearth below the taphole level are still very limited.^{3,27–29)} Therefore, it is necessary to investigate the skull to reveal its formation mechanism and guide the blast furnace operation.

In this paper, firstly, the residual thickness and erosion profile of carbon brick are investigated in detail during the overhaul of a Chinese 2 800 m³ blast furnace. Subsequently, the microstructure, composition as well as mineral phases of the damaged carbon brick and skull are studied with samples obtained from different heights of the hearth. Finally, the formation mechanism of skull and brittle layer is discussed.

2. Samples and Methods

2.1. Introduction of Blast Furnace and the Sampling Position

The relevant parameters of the studied blast furnace have been described in detail in our previous work.³⁰⁾ The furnace bottom was lined with semi-graphite carbon brick, microporous carbon brick and ceramic pad from bottom to top, as shown in Fig. 1 (a). The linings of hearth sidewall were microporous carbon brick and ceramic cup, of which 1–3 layers were Wupeng carbon brick and 4–13 layers were carbon brick manufactured by SGL Group (hereinafter referred to as SGL carbon brick). Carbon brick or skull (a layer of solidified matters attached on the inner surface of carbon brick, see Fig. 1(b)) in the hearth at different heights (S4, S9 and S11) were sampled and investigated after blow-out and cool-down of the furnace. All the carbon brick samples were obtained from the brittle layer (cracked and disintegrated region, see Fig. 1(b)) at the hot surface of carbon brick at different heights.

2.2. Analysis Methods and Sample Preparation

The mineral phases, microstructure and chemical composition of the sampled carbon brick and skull were examined using X-ray diffraction (XRD, Bruker D8 ADVANCE, Germany), scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS, Zeiss Evo18 Special Edition, Germany) and X-ray fluorescence (XRF, Shimadzu XRF-

Fig. 1. Structure and sampling positions of hearth bottom. (a) Schematic of the hearth bottom; (b) Photo of the brittle layer in the carbon brick and skull. (Online version in color.)

1800, Japan), respectively. Small pieces were cut from the samples under dry conditions and mounted in resin. The polished samples were coated with carbon and examined using SEM-EDS for microstructure analysis and element mapping. The samples were crushed to passing less than 74 microns and then analyzed via XRD and XRF for mineral phase analysis and chemical composition analysis, respectively. XRD spectra were obtained using Cu ($K\alpha$) radiation. During XRD analysis, samples were scanned with 2θ in the range of 10 to 90 degree at a scan rate of 5 degree/minute.

3. Results and Discussion

3.1. Investigation of the Refractory Damage in the Hearth Bottom

The residual thickness of the hearth brick is shown in Fig. 2. The remaining thickness of carbon brick is highly inhomogeneous in the height and circumferential direction. In the circumferential direction, the sidewall erosion in the range of 3.6 m (an interval of 3 tuyeres) from the tapholes (TH2, TH3 and TH1) and the No. 15 tuyere is more serious, especially near the TH2 and TH3 tapholes, as shown in Figs. 2 and 3(a). It suggests that flow of molten iron which moves toward taphole is one of the main reasons for sidewall erosion. The minimum residual thickness of carbon brick is about 200 mm. In the height direction, the erosion of the carbon brick below the central line of taphole is more serious than that above the central line of taphole, especially

Fig. 2. Residual thickness of the hearth brick; (Measured according to the position of tuyere). (Online version in color.)

Fig. 3. Erosion profiles of hearth bottom of blast furnace. (a)–(b) Sidewall erosion profile; (c) Bottom erosion profile. (Online version in color.)

at the distance of 1.0–2.0 m (at the level of layers 9 to 10) under the taphole. That is, the erosion of hearth sidewall is “mumps face” type erosion, as shown in Fig. 3(b). The erosion thickness of ceramic pad gradually increases from 100 mm at the periphery part to 470 mm at the central part, that is, the erosion type of bottom is “bowl type”, as shown in Fig. 3(c). The erosion profiles of the hearth bottom under No. 16 and No. 4 tuyeres are shown in Fig. 1.

3.2. Microstructure Analysis of Virgin SGL Carbon Brick

The microstructure and XRD spectra of the virgin SGL

Fig. 4. Microstructure of the virgin SGL carbon brick. (Online version in color.)

Fig. 5. XRD spectra of the original SGL carbon brick.

carbon brick are shown in Figs. 4 and 5, respectively. It can be seen that the SGL carbon brick is mainly composed of C, SiC and Al_2O_3 as well as a small amount of $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ (mullite). SiC, Al_2O_3 and $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ fill in the pores and matrix of carbon brick. Those matters result in an increased particle packing density and decreased mean pore diameter to improve the wear and corrosion resistance to the liquid iron and harmful elements. Overall, SGL carbon brick is dense with micro pores and low apparent porosity.

3.3. Microstructure of Hot Surface of Carbon Brick at the Level of Layer 9

The macrostructure and XRD spectra near the macro crack of SGL carbon brick at the level of layer 9 are shown in Figs. 6 and 7, respectively. The residual carbon brick cracked with numerous laminations in parallel with the hot surface of the brick, as shown in Figs. 6 and 1(b). The width of the largest crack is about 2 mm. The yellow matter filled

Fig. 6. Macrostructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

Fig. 7. XRD spectra of carbon brick near the macro crack at the level of layer 9.

Fig. 8. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

in macroscopic cracks and its thickest thickness is about 4 mm, as shown in Fig. 6. XRD analysis of the yellow matter showed that the phase was mainly ZnO, as shown in

Fig. 9. XRD spectra of hot surface of SGL carbon brick at the level of layer 9.

Fig. 10. Microstructure of SGL carbon brick at the level of layer 9. (Online version in color.)

Fig. 7. It suggests that the Zn vapor diffused into carbon brick along the open pores and reacted with blast furnace gas to form ZnO. Besides, KAlSiO₄ and Zn₂SiO₄ were also detected as small peaks with lower intensity.

The microstructure and XRD spectra of hot surface of SGL carbon brick at the level of layer 9 are shown in Figs. 8 and 9, respectively. It can clearly be seen that K and Zn penetrated into the carbon brick through the pores and reacted with the virgin minerals to form new phases comprised of K–Al–Si–O and Zn–Si–O compounds, as shown in Fig. 8. The new formed phases were mainly observed at the pores and cracks. Zn₂SiO₄ was present in various morphologies including prism and pyramid shapes. Clear peaks of KAlSiO₄, Zn₂SiO₄, ZnO and ZnAl₂O₄ were identified by XRD, while the peaks of SiC, Al₂O₃, and Al₆Si₂O₁₃ corresponding to the phases in the virgin brick disappeared, as shown in Fig. 9. Besides, KCl was observed in the carbon brick, as shown in Fig. 8. However, the peaks of KCl were not confirmed in XRD spectra due to the detection limit of the apparatus or the absence of KCl in the sample used for the XRD analysis. The melting point of KCl is 770°C. The

presence of KCl in carbon brick indicates that the sampling position temperature is lower than 770°C during normal production of blast furnace. But the boiling points of Zn and K are 1 068°C and 956°C, respectively, under an ambient pressure of 400 kPa (blast pressure) atmosphere. Accordingly, it can be inferred that K and Zn react with the minerals of carbon brick in a liquid form in this region.

The microstructure of SGL carbon brick at the level of layer 9 is shown in **Fig. 10** (the sampling position see Fig. 6). A lot of ZnO, KAlSiO_4 and Zn_2SiO_4 were observed in the carbon brick, indicating that the minerals in the virgin

Fig. 11. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

Fig. 12. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

carbon brick react with the foreign elements K and Zn to form new phases. It can be seen that a layer of ZnO and KAlSiO_4 with thickness of 600 micron was found in the hot face of carbon brick. Careful observation shown that there were many micro cracks on the carbon matrix, and K was detected around the cracks. This may be resulted from K inserting into the graphite layer of carbon brick to form interlayer compounds.

The microstructure of hot surface of SGL carbon brick at the level of layer 9 is shown in **Figs. 11–15**. It can be seen that ZnO, Zn_2SiO_4 , KAlSiO_4 and ZnS were observed in the cracks of carbon brick. Previous study¹⁷⁾ shown that the volume expansion from Zn to ZnO and ZnS was determined to be 54% and 83%, respectively. The volume expansion during the transformation of K to KAlSiO_4 was estimated to be 30–50%.³¹⁾ Accordingly, K and Zn penetrating into the carbon brick contribute to the formation of micro cracks

Fig. 13. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

Fig. 14. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

Fig. 15. Microstructure of hot surface of SGL carbon brick at the level of layer 9. (Online version in color.)

in the carbon brick due to the higher volume expansion of reaction products, as shown in Figs. 11–15. The ZnO is mainly present in hexagonal prism morphology, as shown in Fig. 11. The nepheline is present in various morphologies including spherical and columnar shapes, as shown in Fig. 14. As shown in Figs. 12 and 15, the compound close to the carbon of the carbon brick was mainly KAISiO₄, while the ZnO was primarily filled between the KAISiO₄ compounds. It can be inferred that first, K penetrates into carbon brick through open pores and reacts with the minerals to produce KAISiO₄ leading to micro cracks; Subsequently, Zn reacts with CO in the blast furnace gas to form ZnO and then the micro crack is further developed. As the ZnO gradually accumulates in the cracks, the micro cracks finally develop into macro cracks, as shown in Fig. 6.

3.4. Microstructure of Hot Surface of Carbon Brick at the Level of Layer 11

The microstructure and XRD spectra of hot surface of SGL carbon brick at the level of layer 11 are shown in Fig. 16. It can be seen that the carbon brick is mainly comprised of C, KAISiO₄, KAISi₂O₆ and Zn₂SiO₄ while the peaks of mineral phases in the virgin brick disappeared. The new phases formed by the K and Zn corrosion result in cracks. It is noteworthy that the absence of ZnO is confirmed in the diffraction pattern of carbon brick, as shown in Fig. 16(c). It indicates that Zn is easier to react with SiC in the

Fig. 16. Microstructure and XRD spectra of hot surface of carbon brick at the level of layer 11. (Online version in color.)

virgin brick and CO to produce Zn₂SiO₄ than that with CO to produce ZnO.

3.5. Microstructure Analysis of Skull at the Level of Layer 4

The microstructure and XRD spectra of skull at the level of layer 4 (above the taphole) is shown in Figs. 17 and 18, respectively. The identified major phases of skull are Ca₂Al₂SiO₇, Ca₂MgSi₂O₇, CaTiO₃ and KAISiO₄. The Ca₂MgSi₂O₇ and Ca₂Al₂SiO₇ are the common minerals in the continuously cooled crystalline blast furnace slag.³²⁾ Therefore, the skull above the central line of the taphole is mainly comprised of solidified blast furnace slag. Although a little amount of Ti is found, it chiefly exists in the form of CaTiO₃, rather than Ti (C, N). The KAISiO₄ observed in the skull may be attributed to the fact that KAISiO₄ deposited in the deadman coke enters into the blast furnace slag with the dissolution of coke carbon into hot metal.³⁰⁾

3.6. Microstructure Analysis of Skull at the Level of Layer 9

The microstructure and XRD spectra of skull at the level of layer 9 (below the taphole) are shown in Figs. 19 and 20, respectively. Clear peaks of Ca₂Al₂SiO₇, Ca₂MgSi₂O₇, Fe,

Fig. 17. Microstructure of skull at the level of layer 4. (Online version in color.)

Fig. 18. XRD spectra of skull at the level of layer 4.

Fig. 19. Microstructure analysis of skull at the level of layer 9. (Online version in color.)

Fig. 20. XRD spectra of skull at the level of layer 9.

Fe_3Si and CaS were identified by XRD. As the density of hot metal is considerably higher than that of blast furnace slag, it is difficult for blast furnace slag to dip below the taphole level directly. The carbon brick at level of layer 9 is located at 0.9 m–1.3 m below the central line of the taphole. The blast furnace slag layer does not descent to this level during normal production. However, the deadman coke subjected to the penetration of slag in the slag layer moves to the salamander. Then the blast furnace slag that penetrated into the pores of the coke is also brought into the salamander indirectly.³⁰⁾ With the dissolution of deadman coke into hot metal, the blast furnace slag in the deadman coke is exposed and attached to the hot surface of the carbon brick below the taphole level under the suitable conditions to

form skull, protecting blast furnace linings from erosion.³⁰⁾ Accordingly, the $\text{Ca}_2\text{Al}_2\text{SiO}_7$ and $\text{Ca}_2\text{MgSi}_2\text{O}_7$ in the skull are derived from blast furnace slag in deadman coke, rather than the ash in the feed coke.

3.7. Formation Mechanism of the Brittle Layer and Skull

Zn vapor, K vapor and blast furnace gas permeate into the carbon brick through the open pores and cracks, and react with the minerals (SiC , Al_2O_3 and $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) of the carbon brick, as shown in reactions (1)–(5). The blast pressure is 400 kPa and the K_2O and Zn loads in the blast furnace are 2.0 kg/tHM and 150 g/tHM, respectively. The K and Zn compounds in the raw materials and fuels are trans-

formed into pure K and Zn vapors when they descend to hearth level.¹²⁾ The K vapor, Zn vapor and CO pressure are about 202 Pa,¹²⁾ 10 Pa and 162 kPa,¹²⁾ respectively. When the ambient pressure is 400 kPa, the boiling points of Zn and K are 1 068°C and 956°C respectively. Under the above conditions, the relationship between Gibbs free energy and temperature for the reactions of K and Zn with carbon brick minerals is shown in **Fig. 21**. The thermodynamic data on chemical reactions (1)–(5) is calculated through Factsage 7.2 thermodynamic software. When the temperature is lower than 1 450°C, the gas and liquid K can react with the minerals to form KAlSiO_4 . When the temperature is lower than 1 068°C and 950°C, the liquid Zn can react with minerals and CO in gas to form Zn_2SiO_4 , ZnAl_2O_4 , and ZnO, respectively. It is worth noting that since the Gibbs free energy of reaction (3) is much smaller than that of reaction (4), it is easier to form Zn_2SiO_4 than ZnO under the same conditions. It is consistent with the previous result of the section 3.4. Although the mineral yield of the carbon brick is about 20%, the KAlSiO_4 , KAlSi_2O_6 , Zn_2SiO_4 , and ZnAl_2O_4 formed by the reaction can promote the formation and development of micro cracks. However, it is not enough to cause cracks with the naked eye in carbon brick,¹²⁾ which confirmed by the alkalis test of carbon bricks in accordance with Chinese standard YB/T 5213-2016.

The chemical composition of minerals in remaining carbon brick is shown in **Table 1**. The content of K_2O and ZnO in the cold surface of the carbon brick is 3.61% and 0.58%, respectively. It indicates that the penetration ability

Fig. 21. Relationship between Gibbs free energy and temperature for the reactions of potassium and zinc with carbon brick minerals. (Online version in color.)

of K into the carbon brick is stronger than that of Zn. The ZnO near the macro-crack and the hot surface of the carbon brick are 69.69% and 41.59%, while K_2O is 3.17% and 9.88%, respectively. It shows that Zn is the main reason for the formation of macro-crack and brittle layer.

The schematic diagram of formation mechanism of brittle layer is shown in **Fig. 22**. There is a temperature gradient in the carbon brick due to the circulation of hot metal and cooling water on both sides of the brick. In the region where temperature of carbon brick is lower than 950°C, liquid K and Zn react with the minerals and blast furnace gas to produce KAlSiO_4 , KAlSi_2O_6 , Zn_2SiO_4 and ZnO as well as a small amount of ZnS and ZnAl_2O_4 . These new phases lead to crack expansion or new cracks due to the higher volume expansion of these corrosion products, as shown in **Figs. 23(a)** and **23(b)**. In the region where temperature of carbon brick ranges from 950°C to 1 068°C, K vapor and liquid Zn react with the minerals and blast furnace gas to produce KAlSiO_4 , KAlSi_2O_6 , Zn_2SiO_4 and ZnAl_2O_4 , leading to crack expansion or new cracks, as shown in **Figs. 23(a)** and **23(b)**. In the region where temperature of carbon brick is higher than 1 068°C, only K vapor reacts with minerals and blast furnace gas to form KAlSiO_4 and KAlSi_2O_6 , resulting in micro cracks, as shown in **Figs. 23(a)** and **23(b)**. However, Zn vapor does not show any major corrosive effects as it does not react with minerals and blast furnace gas.

The new phases formed in the carbon brick further enlarge and expand the cracks or pores. Meanwhile, it promotes the deposit of ZnO in the cracks and open pores where the temperature is lower than 950°C. With the continuous deposition of ZnO, micro cracks expand into macro cracks and the carbon brick is divided into small pieces, as shown in **Figs. 23(c)** and **23(d)**. With the continuous development of **Figs. 23(a)–23(d)** process, a brittle layer is occurred in the carbon brick where the temperature is lower than 950°C, as shown in **Fig. 23(e)**.

With time elapsing, the minerals of the carbon brick in the region where the temperature is higher than 950°C reacts completely with K or Zn. The volume expansion accompanying the reaction leads to the generation of many micro cracks. Thus the carbon particles in those region is separated into many microscopic pieces by the new phases, leading to carbon brick becoming thoroughly disintegrated and crumbly. Finally, the fine layer is formed, as shown in **Fig. 23(e)**.

The schematic diagram of formation mechanism of skull is shown in **Fig. 23**. When the temperature of carbon brick contacted with blast furnace slag is lower than the melting

Table 1. Chemical compositions of minerals in carbon brick (mass percent).

Item	SiO_2	Al_2O_3	ZnO	K_2O	SO_3	Fe_2O_3	PbO	Others
Cold surface	64.67	15.78	0.58	3.61	3.37	9.02	0.01	2.96
Near macro crack	14.27	6.75	69.69	3.17	3.18	1.52	0.66	0.76
Hot surface	23.77	15.82	41.59	9.88	0.00	3.78	1.93	3.24

Fig. 22. Schematic diagram of formation mechanism of brittle layer. (Online version in color.)

Fig. 23. Schematic diagram of formation mechanism of skull. (Online version in color.)

point of blast furnace slag, the blast furnace slag interacts with the carbon brick minerals to form skull, as shown in Fig. 23. In the hearth, the carbon in the molten iron is unsaturated. Therefore, the carbon in the carbon brick and deadman coke will be dissolved into the molten iron, so that minerals in carbon brick and blast furnace slag infiltrated into deadman coke are directly exposed to the molten iron.³⁰⁾ When the temperature carbon brick soaked in the iron layer is lower than the melting point of the blast furnace slag, the blast furnace slag derived from deadman coke interacts with the carbon brick minerals to adhere to the hot surface of the carbon brick protecting the carbon brick from the erosion of molten iron, as shown in Fig. 23. In addition, when the temperature of the skull or carbon brick is lower than the melting point of the molten iron, the molten iron will also solidify to form skull, as shown in Fig. 23.

4. Conclusions

- (1) The remaining thickness of carbon brick is highly

inhomogeneous in the height and the circumferential direction. In the circumferential direction, the sidewall erosion in the range of 3.6 m from the tapholes is more serious. In the height direction, the carbon brick at 1.0–2.0 m below the central line of the taphole is more serious. The erosion of hearth bottom is “mumps face+ bowl” type erosion.

(2) The minerals of the carbon brick used for more than nine years are mainly composed of KAlSiO_4 , KAlSi_2O_6 , Zn_2SiO_4 and ZnO as well as a small amount of ZnS , KCl and ZnAl_2O_4 . Micro cracks resulted from the KAlSiO_4 , KAlSi_2O_6 , Zn_2SiO_4 and ZnAl_2O_4 are the inducement of formation of carbon brick brittle layer. The main reason for the formation of macro-cracks and brittle layer in carbon bricks is that the reaction product of liquid Zn and CO in gas continuously accumulates in the cracks. The brittle layer of carbon bricks mainly occurs in the region where the temperature of carbon bricks is lower than 950°C .

(3) The skull above the central line of the taphole is mainly composed of $\text{Ca}_2\text{Al}_2\text{SiO}_7$, $\text{Ca}_2\text{MgSi}_2\text{O}_7$, CaTiO_3 and KAlSiO_4 . The skull below the central line of the taphole is

primarily comprised of $\text{Ca}_2\text{Al}_2\text{SiO}_7$, $\text{Ca}_2\text{MgSi}_2\text{O}_7$, CaS , Fe and Fe_3Si .

(4) The blast furnace slag can be present below the central line of the taphole and can adhere to the hot surface of the carbon brick to isolate the direct contact between the molten iron and the carbon brick. The blast furnace slag phase in the skull below the central line of taphole is derived from the blast furnace slag that penetrates into the deadman coke.

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