Migration Behavior of K, Na, S, Ti in Hearth of a Commercial Blast Furnace

Hengbao Ma, Zhengjian Liu*, Jianliang Zhang, Tianlu Gao, Yanbing Zong, Ziyu Guo and Kexin Jiao

* Corresponding author. E-mail: liuzhengjian@126.com

Received date: March 13, 2022
Accepted date: June 14, 2022
Advance published date: July 18, 2022

DOI: https://doi.org/10.2355/isijinternational.ISIJINT-2022-097

Please cite this article as:
https://doi.org/10.2355/isijinternational.ISIJINT-2022-097
Migration behavior of K, Na, S, Ti in hearth of a commercial blast furnace

Hengbao Ma\textsuperscript{1)}, Zhengjian Liu\textsuperscript{1) *}, Jianliang Zhang\textsuperscript{1,2,3)}, Tianlu Gao\textsuperscript{1)}, Yanbing Zong\textsuperscript{1)}, Ziyu Guo\textsuperscript{1)}, Kexin Jiao\textsuperscript{1,3)}

1) School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, P.R. China.
2) State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, P.R. China.
3) Research institute of macro-safety science, University of Science and Technology Beijing, Beijing 100083, P.R. China.

* Corresponding author: Zhengjian Liu

Email: liuzhengjian@126.com
Address: 30 Xueyuan Road, Haidian District, Beijing, 100083, P. R. China

Hengbao Ma: mhb0306@163.com
Zhengjian Liu: liuzhengjian@126.com
Jianliang Zhang: zhang.jianliang@hotmail.com
Tianlu Gao: gtxiaogao@163.com
Yanbing Zong: zongyb@ustb.edu.cn
Ziyu Guo: gzygzy34510@163.com
Kexin Jiao: jiaokexin@ustb.edu.cn
ABSTRACT: In-depth understanding of the existence state and migration behavior of K, Na, S, Ti in the BF hearth is essential to improve the campaign life and optimize the operation process of the blast furnace. In the study, deadman and carbon brick samples were extracted along the radial direction from a large commercial BF during dissection investigation. The microscopic morphology of the samples and the migration behavior of K, Na, S, Ti were analyzed. It was found that a layer of minerals existed on the surface of deadman coke in hearth, and high melting temperature phases such as CaS and TiN as well as slag with high aluminum were existed at the coke-slag-iron interface. K, Na compound present widespread in the deadman coke and carbon brick. The formation of mineral layer reduced the coke dissolution rate, thereby delaying the renewal rate of the deadman. With the dissolution of coke, minerals flow out from the surface of coke and precipitate as alumina and MgAl$_2$O$_4$ spinel, which reduces the voidage of the deadman. Meanwhile, slag is sufficiently desulfurized with the iron to form a large amount of CaS accumulation at the hearth sidewall, which intensifies the iron circulation and increases the erosion of carbon brick. When the slag is in contact with the refractory, the K, Na contained in the slag provides a source of alkalis attack on the carbon bricks, and the Ti in the slag provides the possibility of forming a protective layer containing titanium on the sidewall of the hearth.

Key words: Deadman, Blast furnace dissection, Trace elements, Migration behavior
1. Introduction

The blast furnace process is the most economically efficient way of ironmaking process, and its operating life is an important factor influencing its economy. And with the development of large blast furnace capacity, the service life of blast furnaces becomes more and more important\(^1,2\). As a key area for storing slag and iron in the blast furnace, hearth is the limiting aspect of the long life of the blast furnace. In recent years, a large number of blast furnace anatomical studies have found that the enrichment of trace elements in the hearth plays a crucial role in the safe operation of the blast furnace hearth\(^3-10\). The cyclic enrichment of harmful elements (K, Na, Zn) in the blast furnace aggravates the erosion of the carbon bricks\(^3-6\) and also deteriorates the metallurgical properties of the coke\(^11, 12\). The increased sulfur content in molten pig iron promotes the erosion of carbon bricks\(^13\). It also tends to form a solid calcium sulfide layer on the coke surface to hinder the carburization process of coke in molten iron\(^14\). In addition, the increase of titanium content in molten iron helps to form a titanium-containing protective layer in the weak area of the hearth\(^7-10\). The addition of titanium ore is often used for hearth maintenance in the later stage of blast furnace operation\(^15\). The reaction behavior of trace elements in the hearth greatly affects safety and stability of the blast furnace.

Therefore, an in-depth understanding of the migration behavior and occurrence state of trace elements in the blast furnace hearth is essential to slow down the erosion rate of carbon bricks and improve the active state of the hearth, which would help to further optimize the blast furnace ironmaking operations. In recent years, there have
been increasing interests in exploring the effects of trace elements on coke properties\textsuperscript{11,12}, carbon brick erosion rates\textsuperscript{13,16} and slag properties\textsuperscript{17,18}. However, due to the unique smelting environment of the blast furnace (high temperature, high pressure, confinement, and multiphase coexistence), the information obtained by experimental studies on the effects of trace elements on the internal state of blast furnaces is still limited. At present, based on the blast furnace dissection, Niu et al.\textsuperscript{19} and Sun\textsuperscript{20} et al. analyzed the mineral composition inside the coke in the deadman of the blast furnace hearth and found small amounts of alkali metal compounds in the minerals. Zhang et al.\textsuperscript{21} analyzed the phase composition of the residual iron in the hearth and found that the residual iron near the carbon brick side contains phases such as Ti\textsubscript{3}N\textsubscript{2}, KAlSi\textsubscript{2}O\textsubscript{6}, and Al\textsubscript{2}O\textsubscript{3}. These studies are important to understand the state of trace elements in the hearth. However, the migration behavior of trace elements between slag-iron-coke and carbon bricks in the hearth has not been clarified. In particular, the effect of trace element migration process in the deadman on hearth activity and carbon brick erosion is not yet clear.

In this study, samples of coke, slag, molten iron, and sidewall carbon bricks were obtained from the blast furnace hearth were examined in detail using SEM-EDS. The distribution state of trace elements in the blast furnace hearth was obtained, and the possible migration behavior of trace elements was proposed, to provide guidance for the safe and efficient operation of the blast furnace.
2. Material and methods

In the paper, the samples were collected from a large commercial blast furnace with a volume of 3200 m$^3$ in China. The blast furnace has 4 tapholes and 32 tuyeres, its hearth diameter is 10.5m, and the depth of salamander is 2.75 m. The blast furnace was put into operation on September 25, 2009, and was shut down for overhaul on May 9, 2020, with a generation of 10 years and 7 months of furnace service. And its operation data are shown in Table 1. The blast furnace was stopped by top water cooling without releasing residual iron, and the coke, iron, slag and refractory materials in the furnace hearth were cut by rope saw. A large number of samples were collected along the radial direction of the hearth (mainly including coke, slag, metallic iron in the deadman, and carbon bricks on the sidewalls of the hearth), located between 1.0-2.0m below the level of the taphole, and its detailed sampling location is shown in Figure 1. Among them, S1 is the iron and coke interface in the dead column, S2 is the slag iron in the gap of the deadman, S3 is the slag-iron mixed phase between the deadman and the carbon bricks on the sidewall of the hearth, and S4 is the damaged carbon bricks on the sidewall of the hearth. Table 2 shows the main components of slag, coke ash and molten iron for one month before blast furnace shutdown.
The collected samples were cut into 20-30mm size specimens by diamond slicing. The samples were fixed by epoxy resin inlay and then ground and polished by silicon carbide paper. The samples were coated with Au and then examined with scanning electron microscope (SEM; FEI Quanta 250, USA) equipped with an energy-dispersive X-ray spectrometer (EDS) for chemical analysis and element mapping.

3. Results and Discussion

3.1 Trace elements in deadman samples

Figure 2 shows the microscopic morphology and elemental distribution of the iron-coke interface in the deadman of the hearth. From Figure 2(a), it can be seen that there is a layer of minerals between the coke and the molten iron, and its EDS pattern shows that the mineral layer contains small amounts of alkalis (K$_2$O and Na$_2$O) (Fig. 2(a)P1). Previously, the enrichment of alkalis was found in the coke in both the cohesive zone $^{22}$ and the tuyere zone $^{23}$, and alkalis were carried into the hearth with the coke descended. The pores inside the coke were filled with the slag phase (Fig. 2(b, c)), and the light gray phase in its slag phase showed CaS (Fig. 2(c)). With the coke gasification reaction and iron carburization reaction, the slag phase penetrates into the interior of the coke along the broken pore wall and reacts with S in the coke ash to form CaS. As the dissolution reaction of coke in molten iron proceeds, the slag phase in the pores of coke collects on the surface of coke and forms a mineral layer (Fig. 2(d)), and the formation of mineral layer reduces the coke dissolution rate in molten iron $^{24}$. At the same time, the formation of minerals also promotes the slag-iron interactions. Fig. 2(d) shows the precipitation of regularly shaped solid particles in molten iron, and the
EDS pattern results show that they are mainly composed of Ti and N (Fig. 2(d) P2), which was also reported by Zhang \(^{21}\). In Fig. 2d, it can be seen that metallic iron is present in the titanium nitride particles and the particles are bonded to each other, which may be caused by the heterogeneous nucleation growth of titanium nitride crystals. The EDS mapping results in Figure 3 show that the slag in the mineral layer is mainly composed of Ca, Mg, Al, Si and S elements. However, the metallurgical coke ash is mainly SiO\(_2\) and Al\(_2\)O\(_3\)\(^{25}\). When the coke enters the hearth through the slag layer from the tuyere, the final slag penetrates the interior of the coke along the pores of the coke, thus modifying the ash inside the coke. The slag phase composition was obtained according to multiple EDS results. As shown in Table 3, there is a significant difference in the average composition of the slag phase in the coke pores and the mineral layer. Compared with the slag in the mineral layer, no alkalis were found in the slag of the coke pores. Previously, both Niu\(^{19}\) and Sun\(^{20}\) found that alkalis were present in some of the coke pores and were not uniformly distributed. Also, during the cooling process of the blast furnace shutdown, the alkalis inside the coke tended to spread to the mineral layer, these may be the reasons for the undetected alkalis in the slag of the coke pores. And the penetration of the final slag caused a decrease in the Al\(_2\)O\(_3\) content and an increase in the MgO content of the slag phase in the mineral layer. Meanwhile, the desulfurization reaction at the slag-iron interface promoted the precipitation of CaS in the solid phase, which led to the decrease of slag basicity in the mineral layer. According to the EDS mapping in Fig. 2 (e), there was a CaS layer at the slag-iron interface, and the formation of solid-phase CaS formed blockage at the interface, which
hindered the carburization reaction between coke and iron\textsuperscript{15}, and made the renewal rate of deadman coke slow down. In addition, the precipitation of solid phases reduced the fluidity of the melt\textsuperscript{26}. The formation of solid particles with high melting points of titanium nitride and calcium sulfide at the slag-iron interface deteriorated the slag-iron fluidity on the coke surface, resulting in the slag-iron less flow from the coke surface. It is also regarded as one of the important causes of hearth deactivation in large blast furnaces. As the main source of sulfur in the blast furnace, controlling the sulfur content in the coke is also an important measure to improve the active state of the blast furnace hearth.

3.2 Trace elements in slag

With the dissolution of coke, part of the slag phase in the coke was retained in the deadman. Figure 4 and Figure 5 shows the microscopic morphology and elemental distribution of the slag phase in the deadman. The slag mainly precipitated columnar and granular mineral phases in Fig. 4(a). The EDS mapping shows that the columnar mineral phase is mainly the enriched phase of Al elements, which is Al\textsubscript{2}O\textsubscript{3}. The granular phase is mainly composed of Mg and Al, which is MgAl\textsubscript{2}O\textsubscript{4}. And Ca and Si elements are mainly in the liquid phase. Previously, dissolution experiments of coke in
molten iron revealed mainly large alumina or calcium aluminate agglomerates in the mineral layer \cite{14,24}. Due to the modification effect of final slag on coke ash, in addition to the formation of alumina, the slag phase also forms high melting point magnesia alumina spinel with MgO (Fig. 5 (a)). The low melting temperature CaO-Al$_2$O$_3$-SiO$_2$ liquid phase was formed under the action of SiO$_2$ in slag (Fig. 5 (a, b) P1, P2). In addition, alkalis were found in the slag (Fig. 5 (a) P1). It can be speculated that with the consumption of coke in the hearth, the alkalis inside coke penetrated the coke residue. Previously, Niu et al. \cite{19} and Sun et al. \cite{20} also found alkalis in the residue of coke from the deadman, which also corroborated the migration process of alkalis in the hearth. In previous blast furnace dissections, it was found that alkalis were enriched at different height levels of the blast furnace \cite{27}, and the accumulation times of K and Na in the blast furnace can reach 50 times \cite{28}. Alkalis could cause deterioration of coke performance \cite{11} and damage to carbon bricks \cite{3-5}. After a large amount of alkalis enters the hearth, it would worsen the active state of the hearth and increase the erosion of carbon bricks.

The phase diagram of the quaternary slag system was drawn based on the composition of the slag in the mineral layer, as shown in Figure 6. It can be seen from Fig.6 that the initial precipitation phase of the slag in the mineral layer is located in the spinel region. With the formation of CaS and the reduction of SiO$_2$, the increase of Al$_2$O$_3$ content in the slag promotes the increase of the precipitation temperature of the
solid phase, and the decrease of basicity is beneficial for the precipitation of Al₂O₃, which is consistent with the results in Fig. 4. The precipitation of high melting point phase in the slag accumulates in the deadman, resulting in the decrease of voidage. Meanwhile, with the movement of the deadman, the slag would also contact with the ceramic refractory at the bottom of the hearth, thereby causing corrosion to the refractory.

Figure 7 and Figure 8 show the microscopic morphology of the sample at the edge of the hearth (S3). From the EDS mapping of Fig. 7, it can be seen that the slag phase is mainly CaO-SiO₂-Al₂O₃ slag system with a large amount of CaS, which is obviously different from the slag phase (S2) in the hearth deadman. A small amount of magnesia-aluminum spinel was also found in Fig. 8. The slag phase in the deadman precipitates high-melting alumina and magnesia-aluminum spinel to form a low-melting CaO-rich slag. The increase of free CaO content in the slag would promote the desulfurization reaction between slag and iron\(^{24}\). The slag desulfurization reaction in the hearth is expressed as follows:

\[
\text{CaO}+[\text{S}]+[\text{C}]=\text{CaS}+\text{CO}
\]

The sulphur in the blast furnace is contained in the molten iron and slag mainly. The increase of the S content in the molten iron would reduce the viscosity of the molten iron and increase the corrosion rate of the molten iron on the carbon bricks\(^{13}\). And increasing the CaO content in the slag in the furnace hearth helps to reduce the S content in the molten iron. However, the formation of large amounts of CaS reduces the slag
fluidity and causes slag to accumulate at the edge of the hearth, thus increasing the molten iron circulation at the edge of the hearth. It is necessary to prevent the formation of large amounts of CaS in the hearth during blast furnace production, taking into account the effect of its stacking at the edge of the hearth. The reduction of the precipitation of high melting point phases in the deadman of the hearth is deserving of further investigation, especially the formation of CaS.

3.3 Trace elements in carbon bricks

Figure 9 shows the microscopic morphology of the broken carbon bricks on the sidewall of the blast furnace hearth. From Fig. 9(a,b), it can be seen that there are obvious holes and cracks inside the carbon brick. The results of their EDS mapping show that the white material inside the carbon brick is mainly composed of K, Na, Al, and Si elements, which could be known as potassium nepheline ($K_2O\cdot Al_2O_3\cdot 2SiO_2$) and leucite ($K_2O\cdot Al_2O_3\cdot 4SiO_2$) phases mainly. The enrichment of potassium inside the carbon brick is more significant relative to the enrichment of sodium (Fig. 9 EDS mapping), which is consistent with the results reported by Qi et al. 29), mainly due to the stronger penetration of potassium to carbon bricks than sodium. The enrichment of alkalis inside the carbon brick can cause carbon brick damage, which mainly depends on the reaction of K and Na with $Al_2O_3$ and $SiO_2$ to form potassium nepheline and
leucite to produce lattice expansion\textsuperscript{30}). The frequent fluctuation of the hearth sidewall temperature makes it easier for the alkalis to penetrate the interior of the carbon brick and intensify the damage of the carbon brick. Previously, the researchers described in detail the mechanism of alkalis erosion of the carbon bricks on the sidewalls of the hearth\textsuperscript{3,4}. Potassium and sodium metal vapors penetrate the interior of the carbon brick through the pores and cracks and react with Al\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} causing the damage of the carbon brick, but the source of potassium and sodium and its presence state in the hearth are not clear. As the only solid raw material in the blast furnace hearth, coke has an alkali enrichment behavior during the descent\textsuperscript{31,32}. After coke dissolution alkalis are endowed in the slag phase (as shown in Fig. 5), which is in contact with the carbon bricks of the hearth sidewalls with the flow of molten iron. In contrast, the alkali evaporation rate in the slag increases with increasing temperature \textsuperscript{33,34}, and when there are fluctuations in the hearth sidewall temperature, the alkalis in the slag vaporize and enrich to the lower temperature region. Moreover, the kinetics of alkalis evaporation from blast furnace slag follows a first order reaction and the rate constant of K\textsubscript{2}O is significantly higher than that of Na\textsubscript{2}O\textsuperscript{34}, which is further evidence that potassium is more readily enriched into the carbon brick. In order to reduce the impact of alkalis on blast furnace carbon brick erosion, the further control the alkali load into the furnace and improvement of the slag discharge alkali capacity should be needed in the actual operation of the blast furnace.
3.4 Migration mechanism of trace elements in hearth

In short, through the analysis of the microscopic morphology and composition of slag, iron, coke, and carbon bricks in the hearth of the blast furnace, the phase distribution in the hearth is clarified. Combined with the internal state of the hearth in the investigation after shut down, the behavior of slag, iron, and coke in the hearth and its influence on the corrosion of carbon bricks can be understood. The estimated reaction process is shown in Figure 10. It can be seen from Fig. 10 that the behavior of coke after entering the hearth is mainly divided into two stages. The first stage is mainly the reaction between slag, iron, and coke in the process of coke dissolution. As the coke dissolves into the molten iron, a mineral layer is formed on the surface of the coke. The formation of minerals slows the dissolution rate of the coke into the molten iron. At the same time, the interface reaction between minerals and molten iron forms two high-melting phases, CaS and carbon nitride. The precipitation of the solid phase is not conducive to the slag phase flowing away from the surface of the coke. The second stage is mainly the reaction between slag, molten iron, and carbon bricks. With the scouring of molten iron, part of the slag flows out from the surface of the coke. The desulfurization reaction between the CaO in the slag and the molten iron forms a large amount of CaS solids. Meanwhile, a large amount of magnesia-aluminum spinel and alumina are also precipitated in the slag, and the accumulation of the solid phase would reduce the liquid permeability of the deadman of the hearth. In addition, the accumulation of slag on the edge of the hearth also intensifies the erosion of the carbon bricks by the circulation of molten iron. While the slag is in contact with the sidewall
of the hearth, the K and Na elements carried by the slag penetrated the inside of the
carbon brick and cause the rupture of carbon brick. The migration of the Ti element
provides a possibility for the hearth to form a titanium-rich protective layer. The above-
mentioned research on the phase and reaction behavior of samples in the hearth deepens
the understanding of the internal state of the hearth, which is significant greatly if the
operation of the blast furnace is optimized and the economic benefits of blast furnace
ironmaking is improved.

5. Conclusions

In the paper, the microscopic morphology of deadman coke and carbon brick
samples obtained from the blast furnace were analyzed. The migration behavior of K,
Na, S, Ti in hearth were discussed. The following conclusions were obtained:

(1) A mineral layer was found on the surface of the deadman coke. The high
melting point CaS and TiN formed at the coke-slag-iron interface, which hindered the
renewal rate of the deadman coke.

(2) A large amount of alumina and MgAl₂O₄ spinel was precipitated in the
deadman slag. The precipitation of the high melting temperature phases are the main
reasons for the poor permeability of the liquid phase in the deadman. A small amount
of K and Na was found in the slag phase.

(3) A large amount of CaS in the slag phase present at the edge of the hearth, which
is mainly formed by the desulfurization reaction between the slag phase and the molten
iron. Its accumulation at the edge of the hearth intensifies the circulation of molten iron and increases the erosion of carbon brick.

(4) A large number of holes and cracks were formed inside the broken carbon bricks. The K and Na penetrate the interior of the carbon brick and silica-aluminates of alkalis were formed, which causing the breakage of the carbon brick. Besides, the enrichment of K inside the carbon bricks is more obvious than Na.

(5) The K and Na contained in the minerals provide a source of alkalis attack on the carbon bricks of the hearth sidewalls. Meanwhile, the Ti carried in the slag provides the possibility of forming a protective layer containing titanium on the sidewall of the hearth.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Acknowledgement
This work was financially supported by National Natural Science Foundation of China (Grant No. 51874025).
REFERENCES


https://doi.org/10.2355/isijinternational.ISIJINT-2019-140


https://doi.org/10.1007/s11663-015-0335-9


https://doi.org/10.1002/srin.200405794

19
THE LIST OF TABLES

Table 1 Blast furnace operation data during the entire operation period, wt%.

Table 2 The main components of slag, coke ash and molten iron before blast furnace shutdown, wt mass%.

Table 3 The composition of the slag phase in the mineral layer and coke pores, wt mass%.
Table 1 Blast furnace operation data during the entire operation period, wt%.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity (t/d/m³)</td>
<td>2.37</td>
</tr>
<tr>
<td>Coke (kg/thm)</td>
<td>368</td>
</tr>
<tr>
<td>Coal (kg/thm)</td>
<td>148</td>
</tr>
<tr>
<td>slag rate (kg/thm)</td>
<td>310</td>
</tr>
<tr>
<td>Blast temperature (°C)</td>
<td>1177</td>
</tr>
<tr>
<td>Hot metal temperature (°C)</td>
<td>1497</td>
</tr>
<tr>
<td>Gas utilization rate %</td>
<td>48.56</td>
</tr>
</tbody>
</table>
Table 2 The main components of slag, coke ash and molten iron before blast furnace shutdown,

<table>
<thead>
<tr>
<th>Item</th>
<th>Wt/%</th>
<th>CaO</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>MgO</th>
<th>S</th>
<th>TiO$_2$</th>
<th>K$_2$O</th>
<th>Na$_2$O</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag</td>
<td>39.07</td>
<td>31.87</td>
<td>16.60</td>
<td>9.06</td>
<td>0.82</td>
<td>1.27</td>
<td>0.27</td>
<td>0.39</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Coke ash</td>
<td>4.22</td>
<td>40.55</td>
<td>31.33</td>
<td>0.84</td>
<td>6.11</td>
<td>2.06</td>
<td>0.59</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Wt/%</td>
<td>Si</td>
<td>S</td>
<td>Ti</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Iron</td>
<td>0.42</td>
<td>0.021</td>
<td>0.095</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

mass%wt%.
Table 3 The composition of the slag phase in the mineral layer and coke pores, mass%wt%.

<table>
<thead>
<tr>
<th>Item</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag in coke pores</td>
<td>30.92</td>
<td>33.56</td>
<td>28.84</td>
<td>6.68</td>
<td>-</td>
<td>-</td>
<td>0.92</td>
</tr>
<tr>
<td>Slag in the mineral layer</td>
<td>28.27</td>
<td>39.11</td>
<td>20.55</td>
<td>10.37</td>
<td>1.50</td>
<td>1.78</td>
<td>0.72</td>
</tr>
</tbody>
</table>
THE LIST OF FIGURES

Fig.1 Internal state and sampling position of BF hearth. S1 is the iron coke interface; S2 is the slag-iron in the deadman; S3 is the slag-iron between the deadman and the carbon brick; S4 is a damaged carbon brick on the side wall of the hearth.

Fig.2 SEM images and EDS diffraction pattern of Iron/Coke samples in deadman: (a) iron-coke interface, (b, c) coke, (d) mineral layer.

Fig.3 SEM images and EDS mapping results of slag-iron-coke interface.

Fig.4 SEM images and EDS mapping results of the interface between Al₂O₃ rich slag phase and MgAl₂O₄ rich slag phase in deadman(S2).

Fig.5 SEM images and EDS diffraction pattern of S2: (a) Al₂O₃ rich slag phase, (b) MgAl₂O₄ rich slag phase.

Fig.6 Quadratic phase diagram of the CaO–SiO₂–Al₂O₃–10.55%MgO system (Factsage 6.4).

Fig.7 SEM image and EDS mapping results of the slag-iron interface in deadman edge samples (S3).

Fig.8 SEM image and EDS diffraction pattern of slag in deadman edge samples (S3).

Fig.9 SEM images and EDS mapping results of carbon bricks on the sidewall of the hearth (S4), (a) microscopic morphology of damaged carbon bricks, (b) taken from image (a). The EDS mapping is the taken for image (b).

Fig.10 Schematic diagram of the migration behavior of the elements in the hearth.
Fig. 1 Internal state and sampling position of BF hearth, S1 is the iron coke interface; S2 is the slag-iron in the deadman; S3 is the slag-iron between the deadman and the carbon brick; S4 is a damaged carbon brick on the side wall of the hearth.
Fig. 2 SEM images and EDS diffraction pattern of Iron/Coke samples in deadman: (a) iron-coke interface, (b, c) coke, (d) mineral layer.
Fig. 3 SEM images and EDS mapping results of slag-iron-coke interface.
Fig. 4 SEM images and EDS mapping results of the interface between Al$_2$O$_3$ rich slag phase and MgAl$_2$O$_4$ rich slag phase in deadman (S2).
Fig. 5 SEM images and EDS diffraction pattern of S2: (a) Al$_2$O$_3$ rich slag phase, (b) MgAl$_2$O$_4$ rich slag phase.
Fig. 6 Quadratic phase diagram of the CaO–SiO$_2$–Al$_2$O$_3$–10.55%MgO system (Factsage 6.4).
Fig. 7 SEM image and EDS mapping results of the slag-iron interface in deadman edge samples (S3).
Fig. 8 SEM image and EDS diffraction pattern of slag in deadman edge samples (S3).
Fig. 9 SEM images and EDS mapping results of carbon bricks on the sidewall of the hearth (S4), (a) microscopic morphology of damaged carbon bricks, (b) taken from image (a). The EDS mapping is taken for image (b).
Fig. 10 Schematic diagram of the migration behavior of the elements in the hearth.