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Strength Estimation of Bosh Coke Based on BF Conditions and Coke Quality

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It is well known that a rise in the Pulverized Coal Injection Rate (PCR) will have more possibility in decreasing the coke rate in a Blast Furnace (BF). However, it also leads to the increase of coke abrasion. Insufficient coke strength will generate more coke fines in the lower BF and result in lower permeability and production of Hot Metal (HM). For understanding the behavior of BF bosh coke at various HM productivities, a coke sampler was used to collect the coke samples at the tuyere level for measuring the coke strength. The difference of sampled coke under the conditions of various HM productivities were explored, and the BF operating conditions and causes of generating more coke fines was correlated by testing the coke abrasion rate after reaction. According to the above analysis results, the relative regression equations had been obtained for sampling coke properties, BF operation conditions and BF permeability. Furthermore, the Coke Strength After Reaction (CSR) quantitative target and its online system at various blast conditions were set to provide some reference for coke and HM production.

Keywords: Blast Furnace (BF), Coke sampling, Bosh coke strength, Coke Strength after Reaction (CSR), Abrasion rate

1. INTRODUCTION

The function of coke in a Blast Furnace (BF) can be roughly divided into heat source, reducing agent and medium through which gas and liquid pass. To decrease the BF fuel cost, the BF operation aims are to promote the Pulverized Coal Injection Rate (PCR) resulting in a reduced coke feed rate. It is necessary to reduce the ratio of coke fines and maintain a certain level of coke quality for a smooth BF operation due to the longer stay of coke inside the blast furnace for increasing the abrasion of coke acting as a BF medium. Inadequate coke strength will make for more coke fines being generated in the lower BF, and increasing gas permeability resistance resulting in the decrease of Hot Metal (HM) productivity. To understand the real messages of coke property, powder coal combustion and hearth cleanliness in the BF, it is an effective method in using the BF tuyere coke sampling. In general, the coke sampling at the BF is under a situation without blow-in, and the sampled coke mainly belongs to BF bosh coke. However, they are usually divided into three radial districts, called raceway zone coke, bird's nest zone coke and deadman zone coke along the hearth radius from the tuyere, and the percentages of coke inside the sampler for the three zones vary with the BF operational conditions.

It was shown that the average particle size of the sampled coke sharply declined, and a dramatic increase occurred in the coke fines at these regions below the cohesion zone to the top of the raceway. Larger amounts of coke fines significantly affected the gas and liquid permeability in the lower part of the BF, and it sufficiently indicated the importance of coke strength[1]. The study of sampling coke in Rautaruukki and Nippon Steel (NSC) showed that the coke strength is lower in front of the raceway, and its strength becomes higher the closer to the BF centre at tuyere level.[2,3] It was also found that the sampling coke strength decreased with the increase of PCR in the POSCO research.[4] In addition, it expressed that the SiO_2 change in the sampling coke was small at higher temperature zones, however, it increased with the decline in temperature of coke at a lower temperature zone[5]. According to the literature[6], the temperature of coke sampled from the tuyere almost remained steady in the raceway zone and it raised with the increase of hearth radius from tuyere in deadman zone. Therefore, the SiO_2 content of sampled coke was virtually not changed in the raceway zone and it increased with the increasing distance from the tuyere in the deadman zone.

For this study on coke reaction rate (or coke abrasion rate), the feed coke was used for simulating the heating and reduction conditions inside a BF to find the relationship between coke reaction rate and particle size. It was shown that coke reaction rate has a critical value, which was defined by the amount of surface reaction of the sampled coke. The coke critical reaction rate was determined to be about 30%, which was according to a reacted (or abrasive) coke surface resulting in a sudden large decrease in coke size[7]. In this study, the carbon-steel pipe of the sampler which has a 200-300 mm diameter was inserted into the furnace to conduct a planned coke sampling at the tuyere level of No.3 and No.4 BF at China Steel (CSC). The sampled coke tests were focused on coke strength and reaction rate to examine bosh coke properties correlating with different BF HM productivities and operating conditions, and finally found a real time formula for CSR with the appropriate BF operation indices.

2. EXPERIMENTAL

Figure 1 shows a schematic diagram of high-temperature tuyere coke sampled for this study, and the sampled coke needed to be cooled to room-temperature for executing the following test and analysis. The entire experimental procedure and research are illustrated in Fig.2.

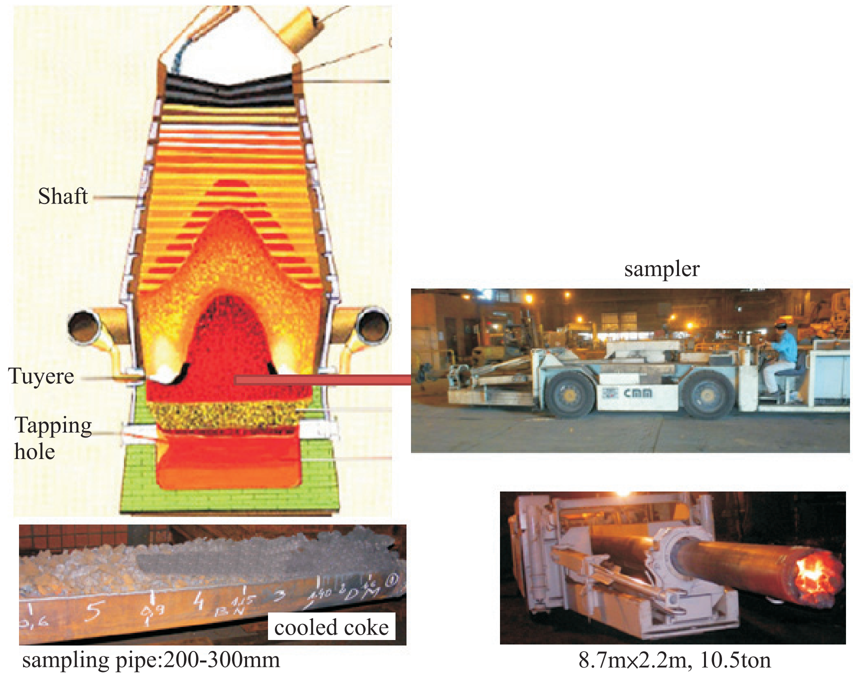

Fig.1. The Schematic diagram of high-temperature coke sampled from BF tuyere.

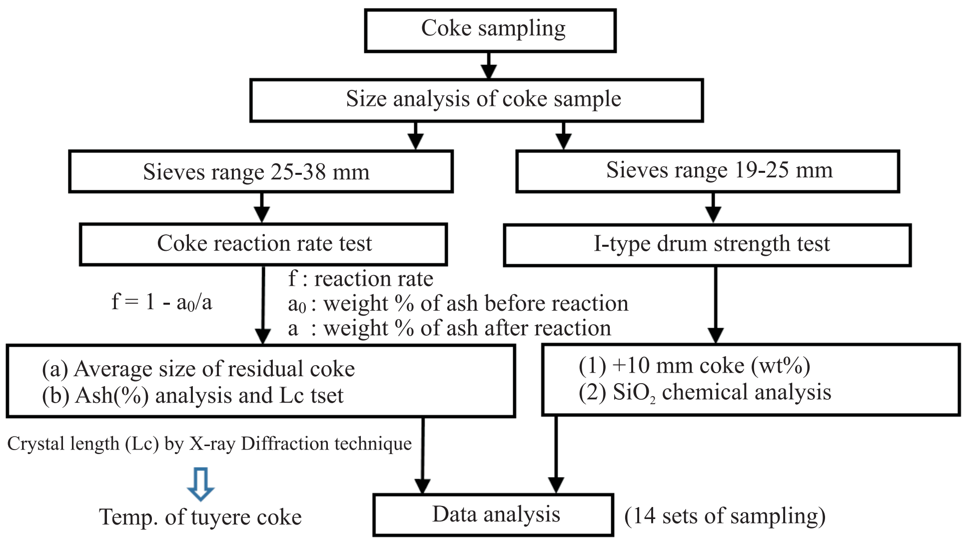

Fig.2. The entire experimental procedure.

2.1 Size analysis of the sampled coke

Each sampling of coke needed to be allocated and numbered carefully corresponding to the real position in the BF, and the entire samples were divided into several segments at intervals of 300mm length. Each sample was screened with 3.35, 15, 25, 38 and 50mm sieves for the size analysis. The +3.35mm coke samples were separated from slag by hand, and the residual one was used for determining the fraction of coke fines.

2.2 Measurement of sampled coke strength

The coke strength can be directly tested by I-type drum used as a measuring CSR device that has experienced high-temperature gasification reaction inside a BF. The coke size ranged from 19mm to 25mm, each segment was loaded into the I-type drum to rotate 600 times, then measuring the fraction of +10mm coke.

2.3 Measurement of sampled coke reaction rate

The coke reaction rate can be also tested by I-type drum used as a measuring Coke Strength after Reaction (CSR) device, and the coke size ranged from 25mm to 38mm, each segment was loaded into the I-type drum to sequentially rotate 100, 200, 500, 1000 times, then the coke size was measured after the completion of the rotation process. In addition, the residual fines that detached from the coke surface were tested to find the ash content and crystalline size (Lc) of the coke. The reaction rate and thickness of the individual layer can be obtained from the ash content, as follows:

The weight of ash before reaction eqals to the weight of ash after reaction.

$$W_0 \cdot a_0 = W \cdot a \qquad (1)$$

$$W = (1-f) \cdot W_0 \qquad (2)$$

$$f = 1-a_0/a \qquad (3)$$

Where W_0: the weight before reaction.
W : the weight after reaction.
a_0 : the weight fraction of ash before reaction.
a : the weight fraction of ash after reaction.
f : the abrasion rate (fraction)

2.4 Measurement of SiO_2 content in the ash

Heating the residual fines that detached from the coke surface to 500℃ for 30 minutes, and then the fines were continuously heated from 500℃ to 815℃ in 60 minutes, then holding at 815℃ for four hours. The SiO_2 content in the residual ash was obtained by chemical analysis.

2.5 Measurement of Lc on estimating tuyere coke temperature[8]

Crystalline size of coke was employed for estimating the temperature of sampled coke inside the BF by the width at half peak height of the diffraction profile (002) for a given sample indicates function of temperature. X-ray diffraction (XRD) techniques have been adopted to measure the Lc, then the calibration curve of the relationship between Lc and heating temperature can be established according to the standard sample, and this curve was used as a standard to estimate the coke temperature.

2.6 Data analysis

Sampled coke strength varies with the PCR and SiO_2 fraction in coke and the radial position sampled from the tuyere. Therefore, the 14 sets of samples from No.3 and No.4 BF of CSC in 2007-2014 were studied on the relationships between coke properties and operating conditions at various BF HM productivities. The main items include:

(A) Measuring the Sampled coke strength under a higher HM productivity (>2 t/m^3-d) and a lower HM productivity (<2 t/m^3-d).
(B) Clarifying the operating conditions and causes for the cases of more coke fines.
(C) Developing the relationships among coke properties, BF operating conditions, and BF gas permeability resistance.
(D) Building the CSR quantitative target and its online system at various operation indices.

3. RESULTS AND DISCUSSION

3.1 I-type drum test for sampled coke strength

It shows as Fig.3 that the relationship between the sampled coke strength by I-type drum and the sampling distance from the tuyere under the conditions of various HM productivities. It was found that these coke strengths were similar at different HM productivities, and the coke strength at the raceway zone was smaller than that of the coke strength at the deadman zone under the conditions of Pulverized Coal Injection (PCI). However, it was almost the same for the entire sampling regions under the case of PCR=0. The reasons for PCI affecting coke strength were expressed as the more carbon solution reaction loss (or boudouard reaction) and the more coke abrasion occurred due to the bosh coke staying in the BF for a longer period of time with PCI, and in this case maybe the surface structure of the abrasive coke was more loose when the bosh coke slowly fell in to the raceway zone near the tuyere, and then reacting with the continuous hot blast blown via the tuyere. However, the original coke located near the deadman zone (at the edge of the raceway) had a higher strength for the reasons that the fines generated from both chemical reaction and physical abrasion on the coke surface was blown by the cycle blast. On the other hand, the bosh coke had a higher replacement inside the

BF without using PCI, and the influence of cycle blast was not clear. Thus, the sampled coke strength in entire sampling regions was similar. It was presented as a curve (a) in Fig.4 that means the relationship between

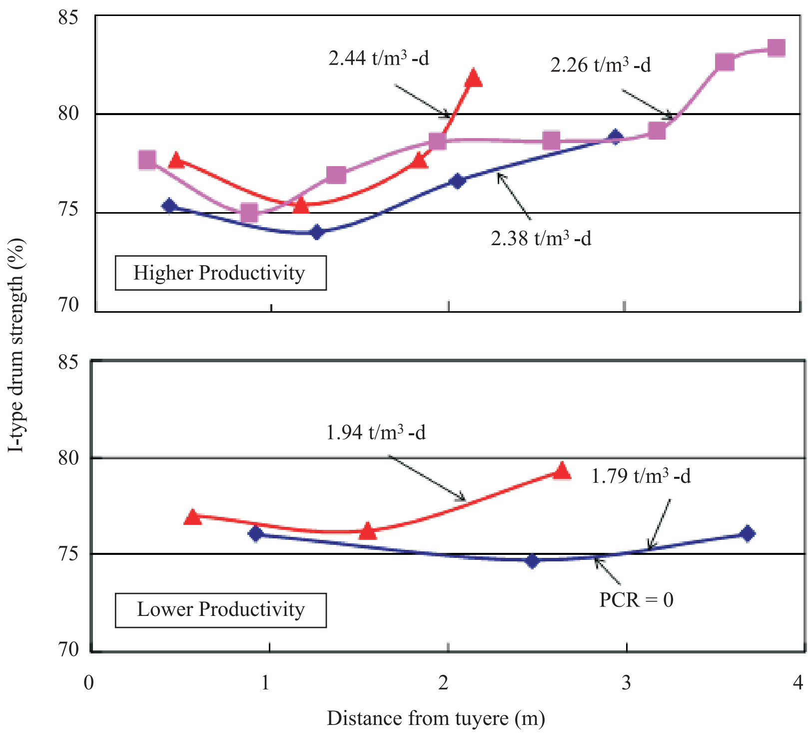

Fig.3. I-type drum strength of coke (%) versus sampling distance from tuyere(m) at various HM productivities.

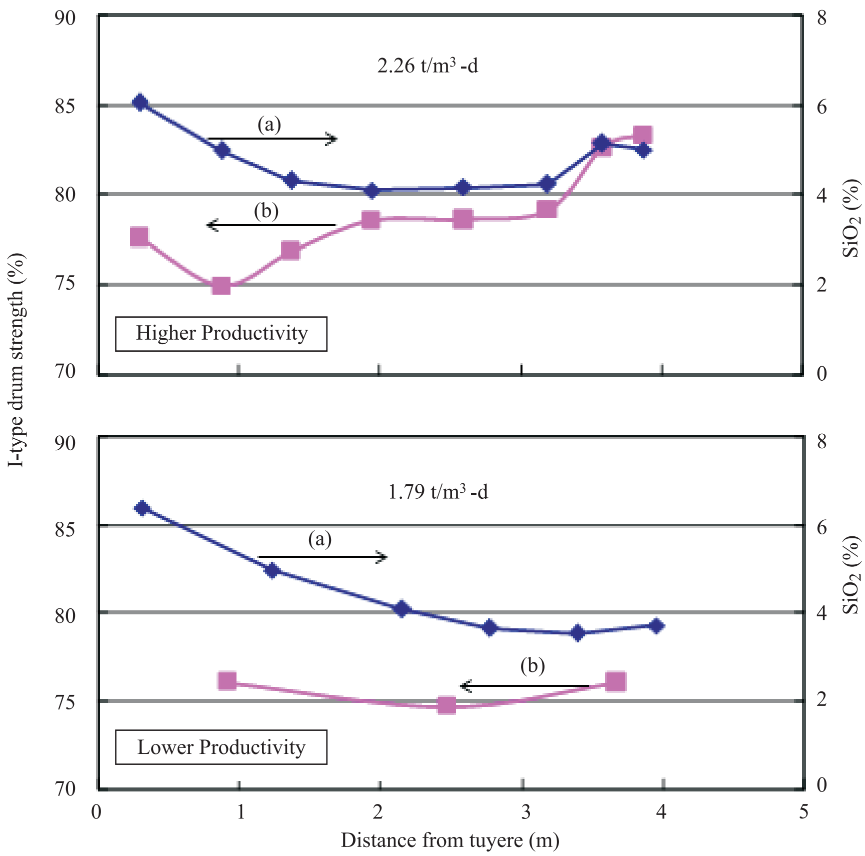

Fig.4. I-type drum strength of coke versus (a) SiO_2 content(%); (b) sampling distance from tuyere(m) at various HM productivities.

SiO_2 content in sampled coke and the sampling distance from tuyere, and it was observed SiO_2 content in entire regions of sampled coke was lower than SiO_2 content in feed coke (6.9%). In general, there is lower SiO_2 content in the coke at tuyere level in the BF, and it maybe related to the reduction reaction of SiO_2 and carbon within the coke at a high-temperature raceway zone[9]. The reaction resulted in producing Si, which quickly dissolved into hot metal while going through the coke bed, and causing a lower SiO_2 content. It was also seen that the results for a higher HM productivity that SiO_2 content of the coke was steady in the raceway zone, but it increased with the increasing sampling distance from the tuyere in the deadman zone. It had not only agreed with the literature[5], but the quantitative results were also expressed in this study. Moreover, the SiO_2 content of the coke in the deadman zone was significantly lower under the condition of PCR=0 at a lower operation of HM productivity than that of a higher HM productivity due to enough heat being generated from using more coke. The comparison of I-type drum strength and SiO_2 content of sampled coke at the BF tuyere level was shown as a curve (b) in Fig.4. It was found that the lower coke strength occurred with less SiO_2 content in the coke, and this implied there were not only the combustion reaction for carbon consumption, but also the SiO_2 reduction reaction simultaneously. Therefore, coke strength was effected due to the carbon consumption inside the core structure of the coke. It indicates from the literature[5] that the slag and iron contents in coke will reduce the I-type drum strength, as shown in Fig.5(a), and the result was in agreement with this study as presented in Fig.5(b). It was deduced that the cokes located in the deadman zone was mixed with BF burden as found in one case of sampled coke due to the condition of falling BF burden before sampling. Thus, it was also found that the content of slag and iron was suddenly ascent (pointed circle). SiO_2 content of this sampled coke was used to verify this deduction that also abruptly increased even more than the SiO_2 in feed coke (Fig.5c) obviously, it got more SiO_2 from the slag derived from falling BF burden. Finally, the test result of I-type drum coke strength was compared with the one in the literature[5], it indicated the coke strength was also dramatically decreased in this case (Fig.5d).

3.2 Abrasion rate test of coke sampled in the raceway zone

The coke abrasion rate in relation to its size can be further calculated when the data from the ash content and residual coke diameter were obtained after the rotating test. Figure 6 presents the relation of abrasion rate versus normalized radius at various HM productivi-

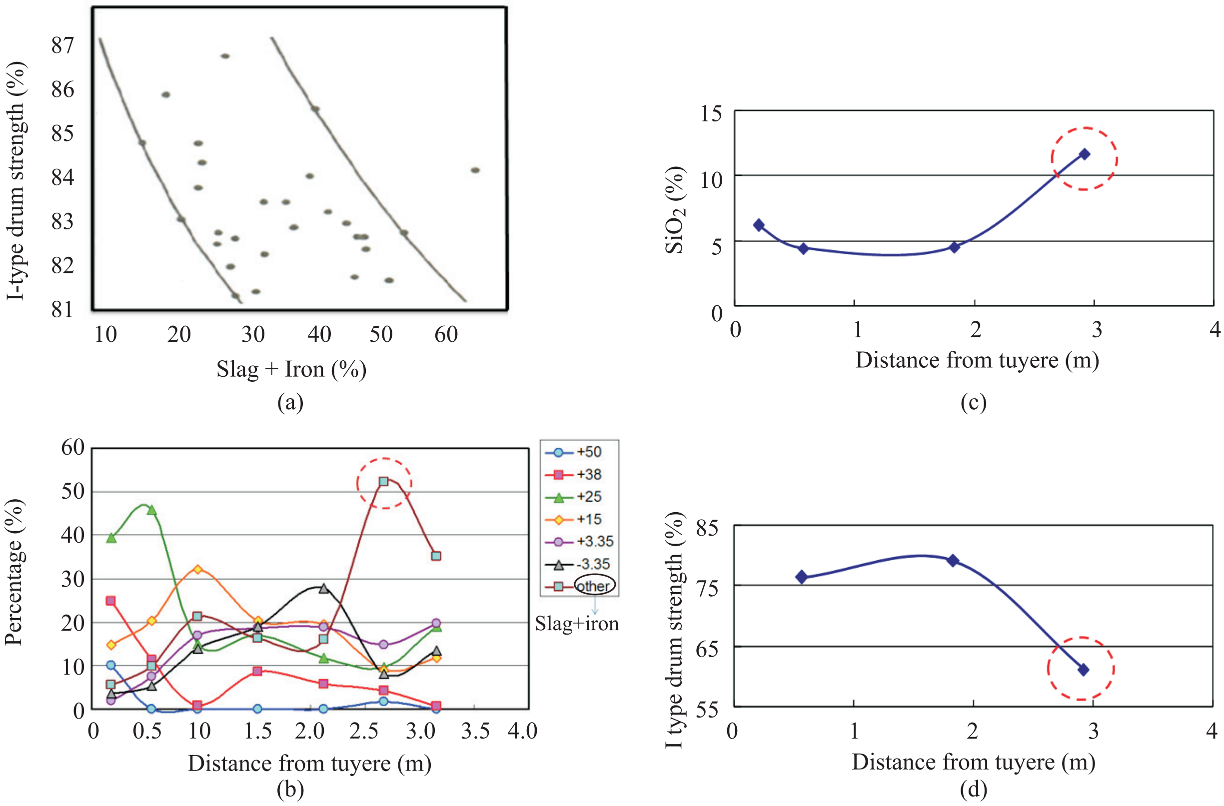

Fig.5. The effects of slag and iron on I-type drum strength of coke.

ties. It was known that the trend of a higher-productivity curve was obviously more distinct than that with a lower-productivity one. In higher HM productivity, the abrasion rate and decreased rate of radius were much higher. And there was more mechanical abrasion to result in producing more coke fines when the surface abrasion rate of the coke started slowing down. On the contrary, the abrasion rate decreased drastically with the occurrence of decreasing radius due to less mechanical abrasion when the surface abrasion rate of the coke suddenly became small. Thus it generated less coke fines in a lower HM productivity. To explicitly describe

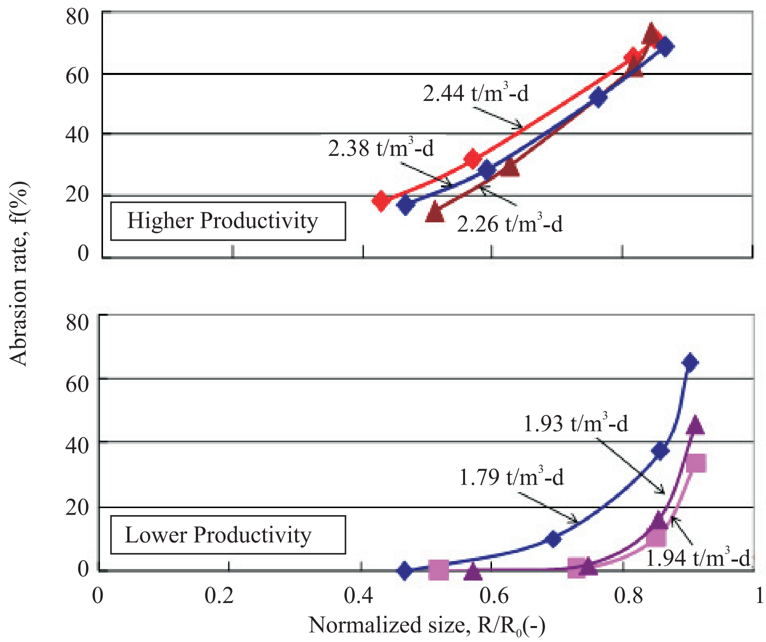

Fig.6. Coke abrasion rate (%) versus normalized coke size (R/R_0)(-) at various HM productivities.

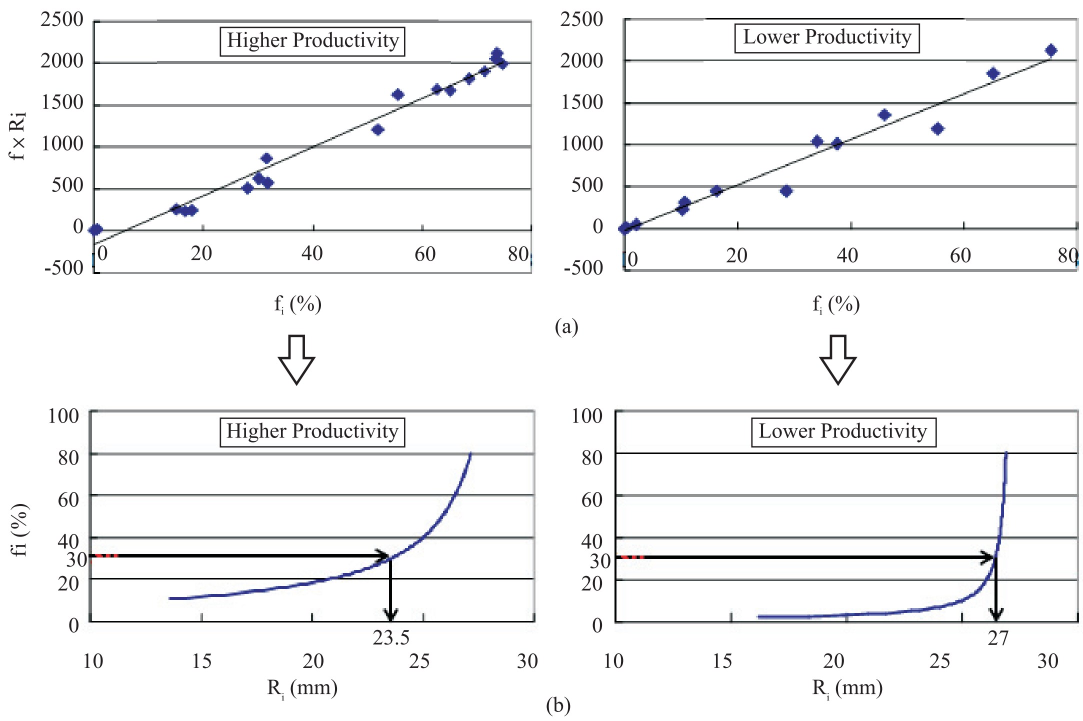

Fig.7. (a) [coke abrasion rate (f_i) × coke radius (R_i)] versus coke abrasion rate (f_i). (b) coke abrasion rate (f_i) versus coke radius (R_i) from equation (4) and (5).

the quantitative relationship of bosh coke abrasion rate and its size, the following equations express the relation of [coke abrasion rate (f_i) × coke radius (R_i)] versus coke abrasion rate (f_i) in this study, as shown in Fig.7(a), equation (4) and (5), and they both correlate coefficient (r^2) in higher and lower HM productivity.

High yield: $f_iR_i = 29.295fi\text{-}172.9$, $r^2 = 0.98$ .... (4)

Low yield: $f_iR_i = 27.2fi\text{-}22$, $r^2 = 0.98$.................. (5)

It was known as Fig.7(b) that the radius decrease of coke was obviously larger at the condition of coke critical reaction rate (30%) for a higher HM productivity, which meant there was a higher abrasion rate on the coke surface to produce more coke fines. The average value on the weight ratio of sampling coke fines (<3.35 mm) was also listed in Table 1, it was seen that the coke fines ranged from 12 to 24 wt% at a higher operation of HM productivity while it only ranged 6-7 wt% at a lower operation of HM productivity. Therefore, the sieving test was in agreement with the abrasion rate test of sampled coke. To clarify the causes of more coke fines generated at a higher operation of HM productivity, the residual ash within the reacted coke was analyzed to obtain the crystal length (Lc), and it was used to investigate the relationship between the coke fines and BF operation with the I-type drum strength of the deadman zone coke, as described in Fig.8. It was actually found that both crystal length (or coke temperature) and I-type drum strength of the deadman zone coke were larger at a higher HM productivity, thus, it was deduced that a higher flame temperature occurred in a higher HM productivity operation. This deduction was also verified with a comparison with BF operation data (flame temperature) on the nearest day before coke sampling (Table 1).

The bosh coke abrasion rate at various residual radius versus sampling coke distance from the tuyere under the conditions of different productivities are displayed in Fig.9. It could be found that there was a greater amount of change in coke abrasion rate at the same particle size for a lower HM productivity, and it was noted that the coke surface wasn't easily abraded resulting in less coke fines. Furthermore, the coke had a greater abrasion (reaction) rate at the sampling depth of 1 to 2 m (raceway zone coke) regardless of a higher or lower HM productivity, but a higher coke reaction rate

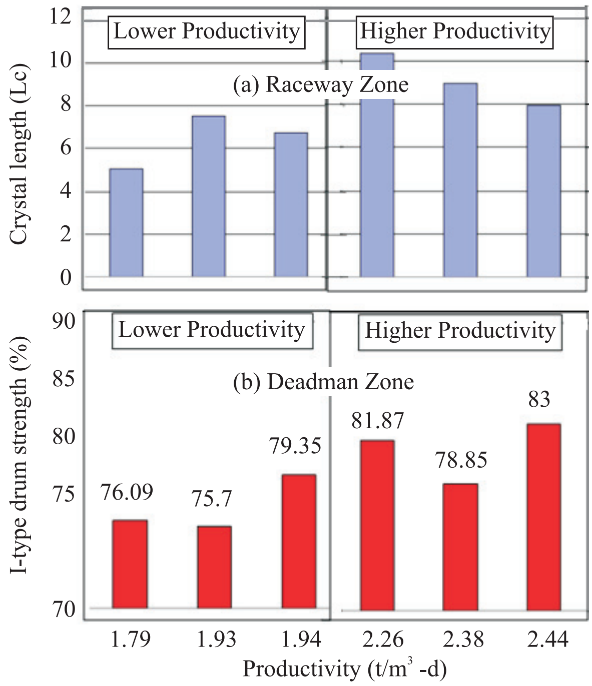

Fig.8. (a) Crystal length of raceway zone coke and (b) I-type drum strength of deadman zone versus HM productivities.

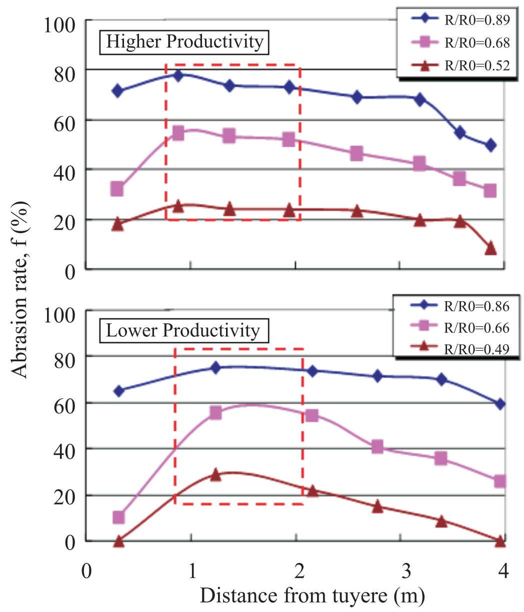

Fig.9. The coke abrasion rate (at various residual radius) versus sampling coke distance from tuyere at various productivities.

Table 1 Bosh coke fines (<3.35mm) ratio, BF HM productivity and flame temperature on the nearest day before coke sampling

	Higher Productivity ←					→ Lower Productivity		
BFs	4BF-1	3BF-1	3BF-2	4BF-2	3BF-3	3BF-4	4BF-3	3BF-5
Productivity (T/M3D)	2.44	2.38	2.35	2.45	2.26	1.79	1.93	1.94
Coke fines ratio (%)	12.1	19.2	23.7	13.1	20.7	6.8	6.8	6.1
Flame temperature (℃)	2100	2283	2217	2141	2197	2183	2049	2055

was only maintained in the deadman zone. Coke reaction rate was supposed to relate with larger blast volume and higher flame temperature. In theory, the higher coke reaction rate occurred due to its more abrasive coke structure which would result in a smaller coke strength. The results in Fig.9 were compared with those of Fig.3, it was known as expected that I-type drum coke strength was opposed to coke reaction rate, as mentioned in the introduction[5].

3.3 Analysis of sampled coke relationship with BF operation

The properties of sampled coke and BF operation data (including feed coke properties, BF operation indices and blast conditions) of the nearest day before sampling were used for correlation analysis in this study, as listed in Table 2. It was pointed out that the negative correlation coefficient of bosh coke fines ratio (CFR) and feed CSR was high enough (-0.92), thus, the accessible CSR was selected to replace the CFR which could only be obtained on the sampling date. It was thought in Table 2, that the DP/V was chosen as a dependent variable, and the higher correlation coefficient such as CSR, $T_{liquidus}$ and PCR were used as the independent variables in this study. A regression equation was obtained by way of normalization (0-1, listed in Table 3) at first and then multiple regression analysis thereafter, as follows:

$$DP/V = -0.238CSR + 0.345T_{liquidus} + 0.586PCR, \quad ...(6)$$

$r^2 = 0.88$, $\alpha < 0.05$

Where DP/V : gas permeability resistance kg-min./cm^2-NM^3),
CSR : feed Coke Strength after Reaction (%),
$T_{liquidus}$: slag liquidus temperature (℃),
PCR : Pulverized Coal injection Rate (kg/tHM).

Equation (6) shows the relationship among DP/V, CSR, Tliquidus and PCR, it was known that DP/V will obviously increase with the decrease of CSR, and the increasing Tliquidus and PCR. The multiple correlation coefficient (r) of this equation was 0.94, indicating that it was in good agreement with its original data. And the significant level (α) of this equation is much smaller than 0.05, indicating that the dependent variable of this regression equation was enough as described by the three independent variables. It is worth mentioning that the $T_{liquidus}$ was derived from the slag fluidity model developed by Shiau[10], which was calculated according

Table 2 Correlation analysis of the properties of sampling coke and BF operation data of the nearest day before coke sampling

	DP/V	CFR	CSR	CRI	M40	M10	MS	PCR	BT	TFT	BF	BV	T_{liq}
DP/V (gas permeability resistance, Kg-min./cm^2-NM	1.00												
CFR (coke fines ratio, %)	0.96	1.00											
CSR (coke strength after reaction, %)	-0.96	-0.92	1.00										
CRI (coke reaction index, %)	0.93	0.87	-0.94	1.00									
M40 (coke strength-1, %)	-0.28	-0.31	0.31	-0.25	1.00								
M10 (coke strength-2, %)	-0.20	-0.19	0.21	-0.18	-0.71	1.00							
MS (coke mean size, mm)	-0.34	-0.48	0.39	-0.29	0.15	0.29	1.00						
PCR (pulverized coal injection rate, kg/tHM)	0.83	0.84	-0.82	0.83	-0.15	-0.34	-0.29	1.00					
BT (blast temperature, ℃)	0.55	0.55	-0.50	0.59	-0.05	-0.22	-0.13	0.77	1.00				
TFT (theoretical flame temperature, ℃)	0.25	0.33	-0.37	0.26	-0.54	0.09	-0.17	0.50	0.18	1.00			
BP (biast pressure, Pa)	0.72	0.73	-0.75	0.85	-0.19	-0.31	-0.31	0.89	0.62	0.48	1.00		
BV (blast volume, NM^3/min.)	0.53	0.57	-0.58	0.69	-0.28	-0.19	-0.28	0.73	0.41	0.59	0.93	1.00	
$T_{liq.}$ (slag liquidus temperature, ℃)	0.91	0.88	-0.88	0.96	-0.18	-0.22	-0.31	0.88	0.68	0.28	0.88	0.73	1.00

Table 3 Normalized data of DP/V, CSR, $T_{liquidus}$, and PCR for the nearest day before coke sampling in 2007-2014

Sampling No	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12	No.13	No.14
DP/V	0.830	0.585	0.623	0	0.170	0.528	0.925	0.698	0.830	0.528	0.189	1	0.453	0.189
CSR	0.337	0.518	0.446	1	0.880	0.663	0.145	0.434	0.361	0.542	0.759	0	0.663	0.723
$T_{liquidus}$	0.976	0.854	0.902	0	0.439	0.756	0.976	0.927	0.976	0.756	0.439	1	0.659	0.683
PCR	0.977	0.743	0.714	0	0.531	0.691	0.977	0.743	0.863	0.714	0.503	1	0.697	0.531

to the five main chemical compositions (CaO, SiO_2, Al_2O_3, MgO, TiO_2) in BF final slag. The required CSR indices of No.3 and No.4 BF were established at different DP/V (0.24-0.28) and PCR (140-180) based on the averaged $T_{liquidus}$ in 2014, as shown in Table 4, and its online system was also developed as shown in Fig.10. From the calculated results listed in Table 4, the higher CSR of feed coke was in need of reaching a lower gas permeability resistance, similarly, it also needed higher CSR with the operation of higher PCR. The monthly data of averaged PCR and $T_{liquidus}$ of December 2014 was used for calculating the necessary CSR of feed coke. It resulted that No.3 BF needs the feed coke whose CSR is larger than 69, and No.4 BF needs the feed coke whose CSR is 70 at least in order to maintain good permeability resistance (0.25). In Figure 10, it indicated the comparison of daily CSR for feed coke in No. 3 BF and calculated real-time CSR in this study during March to May 2015, the results show that a half of the feed coke is close to the need coke.

4. CONCLUSIONS

4.1 Sampled coke strength in tuyere level

1. The higher the sampled coke strength, the larger the loss of averaged size coke. Raceway coke strength was smaller than deadman zone coke strength under the conditions with PCI, but it was almost the same for the entire sampling regions under the case of PCR=0.
2. SiO_2 content in sampled coke may reflect its strength, the less SiO_2, the lower the coke strength.

4.2 Sampled coke abrasion rate in tuyere level

1. The higher the sampled coke reaction rate, the larger the loss of averaged coke size. There was higher abrasion on the coke surface to produce more coke fines at a higher HM productivity, but it was opposite at a lower HM productivity.
2. The reason of more coke fines at a higher HM productivity was the higher flame temperature, and the I-type drum coke strength was opposed to coke reaction rate.

4.3 Sampled coke properties relationship with BF operation

1. The required CSR index of No.3 and No.4 BF, and its online system were established by using the sampled coke properties at different gas permeability resistance and PCR to provide some reference for the HM and coke production.
2. The monthly data of averaged PCR and $T_{liquidus}$ of 2014/12 was used for calculating the necessary CSR of feed coke. It resulted that No.3 BF needs feed coke with a CSR larger than 69, and No.4 BF needs the feed coke with a CSR of at least 70 in order to maintain good permeability resistance (0.25).

Table 4 The required CSR indices of No.3 and No.4 BF at different DP/V (0.24-0.28) and PCR (140-180) based on the averaged $T_{liquidus}$ in 2014

BFs	3BF/2014/ $T_{liquidus}$=1410℃									4BF/2014/ $T_{liquidus}$=1415℃								
DP/V	0.24			0.26			0.28			0.24			0.26			0.28		
PCR	140	160	180	140	160	180	140	160	180	140	160	180	140	160	180	140	160	180
CSR		70.7		68.0	69.5	70.7	61.0	62.5	64.0		70.7		68.8	70.3	70.7	61.7	63.2	64.8

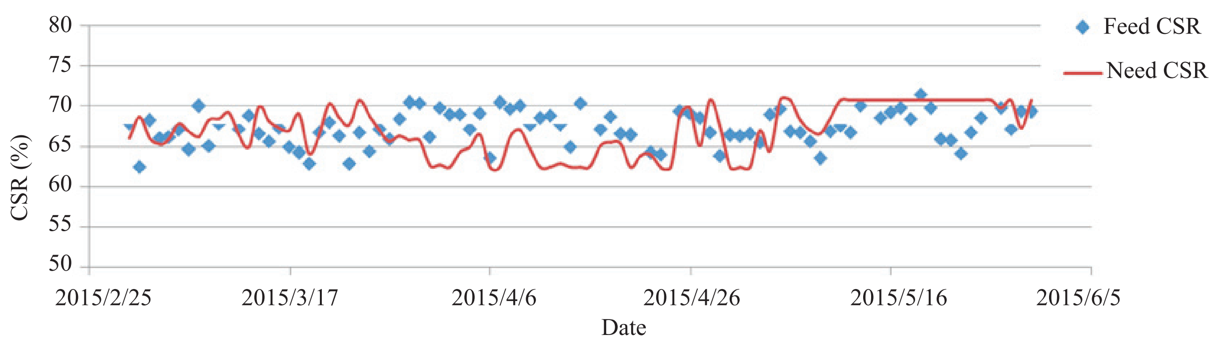

Fig.10. Comparison of daily CSR for feed coke in No. 3 BF and calculated CSR in this study during 2015/3-2015/5.

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