Economical and Efficient Protection for Blast Furnace Hearth

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In order to clarify the erosion mechanism of carbon brick and realize the economical and efficient protection for blast furnace hearth at the end of the service. The damaged carbon bricks were sampled from a commercial blast furnace, the microstructure of the damaged carbon bricks was analyzed through SEM and EDS. The carbon undersaturation degrees of molten iron for different volume blast furnace were calculated, the dissolution and the penetration were considered as the reasons for the erosion of carbon brick. A model of economical and efficient protection for hearth was established based on various factors, the economy of protection raw material and the protection effect can be evaluated through the model. The model guides the selection of the economical protection raw material according to the evaluation, the reasonable operation can be obtained according to the calculation of the fettling rate.

KEY WORDS: blast furnace; economical and efficient protection; carbon undersaturation degree; economic evaluation; fettling rate.

1. Introduction

The accidents of blast furnace (BF) hearth were reported frequently.^{1,2)} The burn out of hearth occurred from small BF (100 m³) to large BF (4 747 m³), hearth had always been the limiting area for long campaign life of BF.³⁾ However, the erosion mechanism of carbon brick was not clear although many dissection investigations were carried out in the past.^{4,5)} Raw materials containing titania charged in BF is the universal measure to prolong the service life of hearth. The injection of titania powder from tuyere and the application of taphole clay containing titania are considered as effective methods, while, the addition of ore containing titania from BF top is announced more convenient.^{6–9)}

Titania content, total iron grade, basicity and price change with the variety of ore. It is the concern for operators to choose the economical ore containing titania for protection.^{10–12)} The effect of titania content on metallurgical properties of the ore was investigated by many papers,^{13,14)} the evaluation of the economy only based on price was concluded to be one-sided, few people synthetically evaluate the economy of the ore containing titania based on the price, the flux amount, the iron production and the slag amount.¹⁵⁾ In addition, the evaluation index of the protection effect is lacking, the stability of the protection effect can't be guaranteed due to the change of operation, the time to increase titanium load becomes the key for operators.^{16,17)}

In the current study, the reasons for the erosion of carbon brick were analyzed, a model of economical and efficient protection for hearth was established based on various

factors, the evaluation index of the protection effect was obtained according to the calculation of the fettling rate.

2. Experimental

2.1. The Erosion Morphology of Carbon Brick

The studied BF (1 780 m³) was blown in on December 30, 2007 and shut down on August 3, 2015. The hearth sidewall was lined with carbon bricks and the ceramic cup, the hearth was dissected after blow-out. The damaged carbon bricks were sampled from the hot face of the hearth, the circumferential and vertical positions of the damaged carbon bricks were shown in **Figs. 1(a)** and 1(b).

The SEM and EDS results of sample 1 are presented in **Fig. 2**, the hot face of the damaged carbon brick is presented in **Fig. 2(a)**. When molten iron is in contact with the carbon brick directly, the penetration of molten iron occurred through the micropore of carbon brick. The molten iron penetrated into the pores of carbon brick, after the pores were enlarged, the molten iron in the pores was joined together **Fig. 2(b)**. Fine cracks formed after the penetration, the embrittlement of carbon brick appeared due to the strength decreased, carbon brick particles will fall off from the matrix.

Microstructures of sample 2 analyzed through SEM and EDS are shown in **Fig. 3**, the surface scanning of interface indicates the carbon brick had been surrounded by molten iron, the high carbon content in molten iron near the interface illustrates that the carburization occurred which demonstrate the erosion of carbon brick was caused by the dissolution of molten iron.

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Fig. 1. The circumferential and vertical positions of the samples.

Fig. 2. Microstructure of sample 1. (Online version in color.)

2.2. The Carbon Undersaturation Degree of Molten Iron in Hearth

Carbon has a great influence on the melting point of molten iron, the precipitation of graphite, the viscosity of molten iron and the erosion carbon brick.^{18,19)} The carburizing reaction begins with the appearance of metal iron, it is known from iron-carbon phase diagram that the saturated carbon content in molten iron is related to the temperature, the amount of carbon to reach the saturation of molten iron is high owing to the molten iron temperature of large BF is high.

In addition to the temperature, the saturated carbon content in molten iron is also related to the composition of molten iron, it can be calculated by the following equation:²⁰⁾

$$[C]_{sat} = 1.34 + 2.54 \times 10^{-3}(T - 273) - 0.35[\%P] + 0.17[\%Ti] - 0.54[\%S] + 0.04[\%Mn] - 0.30[\%Si] \quad \dots (1)$$

where $[C]_{sat}$ is the saturated carbon content in molten iron, %; T is the temperature of molten iron, K; $[\%i]$ is the element content of molten iron.

The calculation results of different volume BF are presented in **Table 1**, the saturated carbon content of different volume BF is about 5%, the content of the carbon is undersaturated compared with the actual carbon content in molten iron. The actual molten iron in hearth had been put into a high temperature tube furnace, and heated to 1 773 K under argon protection, the carbon content increased with the time.

Both theoretical calculation and experiment show that the

Fig. 3. Microstructure of sample 2. (Online version in color.)

Table 1. The carbon undersaturation degrees of different volume BF.

V, m ³	T, °C	C, %	Si, %	Mn, %	P, %	S, %	Ti, %	C _{sat} , %	δ, %
450	1 479	4.57	0.51	0.29	0.105	0.026	0.051	4.91	6.92
1 050	1 483	4.68	0.32	0.32	0.100	0.057	0.102	4.98	6.02
1 780	1 490	4.84	0.32	0.28	0.099	0.032	0.034	4.99	3.01
2 600	1 505	4.87	0.46	0.15	0.093	0.030	0.118	5.00	2.60
3 200	1 509	4.83	0.35	0.28	0.092	0.027	0.042	5.04	4.17
4 747	1 508	4.89	0.44	0.17	0.081	0.026	0.045	5.01	2.40

carbon content is undersaturated in hearth, the carbon undersaturation degrees of different volume BF can be calculated:

$$\delta = \frac{[C]_{sat} - [C]_{act}}{[C]_{sat}} \times 100\% \quad (2)$$

where δ is the carbon undersaturation degree, %; $[C]_{sat}$ is the saturated carbon content in molten iron, %; $[C]_{act}$ is the actual carbon content in molten iron, %.

Table 1 presents that carbon content is undersaturated in hearth for all BFs, while the carbon undersaturation degree is related to the volume of BF, the actual carbon content of molten iron increases with the increase of BF volume (Fig. 4), therefore, the carbon undersaturation degree of large BF is lower which may be the reason of long service life for large BF.

2.3. The Erosion Process of Carbon Brick and the Formation of Titanium Bearing Protective Layer

The erosion of carbon brick can be divided into four processes (Fig. 5): 1) Molten iron contacts the carbon brick

Fig. 4. The carbon undersaturation degrees of different volume BF. (Online version in color.)

directly; 2) The penetration of molten iron occurs through the micropore of carbon brick; 3) The embrittlement of carbon brick appears due to the strength decreases, carbon brick particles will fall off from the matrix; 4) The dissolution of carbon brick occurs owing to the carbon content of molten iron is undersaturated in hearth. The four processes constitute a cycle which causes the erosion of carbon brick gradually.

The protective layer should be established to insulate the molten iron and the carbon brick. After the addition of materials containing titania, the titania is reduced to titanium and dissolved into the molten iron. As the operational condition of the BF change, molten iron containing titanium will migrate to the low temperature region of the hearth. It can crystallize in the form of TiC and TiN or Ti(C, N) solid solution on the hot face of the damaged carbon brick when titanium in molten iron is saturated, these high melting point materials gradually form a protective layer to delay the erosion of carbon brick.

Fig. 5. Schematic diagram of the erosion process. (Online version in color.)

3. The Model of Economical and Efficient Protection for Hearth

3.1. Economic Evaluation of Raw Material for Protection

The economic evaluation was established based on the titanium content of molten iron, the distribution ratio of titanium, the composition of raw material, the price of raw material and the operation of BF. The calculation process is summarized in Fig. 6.

Firstly, the lower limit of the effective titanium content in molten iron is obtained according to the thermocouple temperature during protection. The maximum titanium distribution ratio (the situation of titanium from slag to molten iron at most) is taken to calculate the titania content in slag. Thus, the economic titanium load can be calculated based on titanium balance.

The total cost consists of four parts: cost of raw material for protection, cost of flux consumption, saving the cost of molten iron and cost of coke consumption. The basic materials remains unchanged, calculate the cost of raw material for protection.

$$\text{Cost of raw material for protection: } P_1 = m_1 \times p_1 \dots (3)$$

where P_1 is cost of raw material for protection, RMB/t; m_1 is the raw material mass for protection, kg/t; p_1 is the raw material price for protection, RMB/kg.

The CaO mass change after adding the titanium resources can be calculated on the premise of keeping the basicity of the slag constant, so the cost of flux consumption can be obtained.

$$\text{Cost of flux consumption: } \frac{m_{P-CaO} + \Delta m_{CaO}}{m_{P-SiO_2}} = R \dots (4)$$

$$P_2 = \Delta m_{CaO} \times p_2 \dots (5)$$

where R is the basicity of slag; m_{P-CaO} is the CaO mass of raw materials for protection, kg; Δm_{CaO} is the CaO mass change after adding the titanium resources, kg/t; m_{P-SiO_2} is the SiO_2 mass of raw materials for protection, kg; P_2 is the cost of flux consumption, RMB/t; p_2 is the CaO price, RMB/kg.

The extra molten iron mass can be calculated through the grade of raw materials for protection as raw materials for protection contain iron, therefore, the cost of saving can be

Fig. 6. Schematic diagram of the economic evaluation. (Online version in color.)

obtained.

$$\text{Saving the cost of molten iron: } m_1 \times TFe / 100 = m_{iron} \dots (6)$$

$$P_3 = m_{iron} \times p_3 \dots (7)$$

where TFe is the grade of iron, %; m_{iron} is the extra molten iron mass, kg/t; P_3 is cost of saving, RMB/t; p_3 is the price of molten iron, RMB/kg.

The impurities brought by the raw materials for protection will increase the amount of slag and consume heat, moreover, the desulphurization is a heat consuming reaction while the heat consumed is provided by coke. The consumption of heat can be calculated based on the mass and composition of the raw materials for protection, therefore, the coke cost can be obtained.

$$\text{Coke cost: } Q = \sum C_i m_i \Delta T \dots (8)$$

$$P_4 = m_{Coke} \times p_4 \dots (9)$$

where Q is the consumption of heat, kJ; C_i is the heat capacity, kJ/(kg·K); m_i is the impurity mass, kg; ΔT is the temperature difference between slag and room, K; P_4 is the cost of coke, RMB/t; m_{Coke} is the mass of coke, kg; p_4 is the price of coke, RMB/t.

$$P = P_1 + P_2 + P_3 + P_4 \dots (10)$$

The total cost P can be used to compare the economy of the raw materials for protection.

3.2. The Protection Effect Evaluation Based on the Fetting Rate

The stability of the protection effect can't be guaranteed due to the change of operation, the time to increase titanium load becomes the key for the operators, the evaluation index of the protection effect is obtained through the titanium balance (Fig. 7).

The fettling rate is defined as the evaluation index of the protection effect:

$$m_{r-TiO_2} = m_{i-TiO_2} - m_{o-TiO_2} \dots (11)$$

$$\Psi = \frac{m_{r-TiO_2}}{m_{i-TiO_2}} \times 100\% \dots (12)$$

where m_{r-TiO_2} is the residual mass of titania, kg/t; m_{i-TiO_2} is the input mass of titania, kg/t; m_{o-TiO_2} is the output mass of titania, kg/t; Ψ is the fettling rate, %.

The protection effect can be evaluated through the fettling

Fig. 7. Schematic diagram of the titanium balance. (Online version in color.)

Table 2. The protection effect evaluation based on the fettling rate.

The fettling rate	The protection effect
$\Psi >> 0$	The carbon brick will be patched quickly
$\Psi > 0$	The carbon brick will be patched slowly
$\Psi \approx 0$	The carbon brick will maintain the status
$\Psi < 0$	The carbon brick will be eroded slowly
$\Psi << 0$	The carbon brick will be eroded quickly

Table 3. The raw materials of a large BF.

Raw materials	TFe	SiO ₂	Al ₂ O ₃	CaO	MgO	S	TiO ₂	TFe+TiO ₂
Sinter	57.40	5.07	1.89	10.22	1.41	0.02	0.18	57.58
Pellet	65.47	3.24	0.61	0.69	1.59	0.01	0.08	65.55
Lump	61.95	3.24	1.81	0.07	0.00	0.01	0.08	62.03
Imported titanium ore	43.44	9.71	5.01	2.33	4.72	0.33	18.60	62.04
Titanium ore	48.00	6.93	5.71	1.37	2.80	0.32	12.00	60.00
Chengde titanium pellet	51.40	6.32	2.37	1.68	1.75	0.02	13.15	64.55

rate as summarized in Table 2: the carbon brick will be patched when the fettling rate is positive, the carbon brick will maintain the status when the fettling rate is approximately equal to zero. However, the carbon brick will be eroded when the fettling rate is negative, it is necessary to adjust the operation to increase the titanium load. In summary, the reasonable operation during protection can be obtained according to the fettling rate.

3.3. The Application of the Model

The raw materials of a large BF are presented in Table 3. The sinter, the pellet and the lump are the basic materials, while the imported titanium ore, the titanium ore and the Chengde titanium pellet are the raw materials for protection. The model can be used to compare the economy of the raw materials for protection.

The lower limit of the effective titanium content in molten iron, the maximum titanium distribution ratio, the titania content in slag and the economic titanium load are shown in Table 4. The basic materials remains unchanged: sinter+pellet+lump+ raw materials for protection, calculate the cost of raw materials for protection. The cost of raw material for protection, cost of flux consumption, saving the cost of molten iron and cost of coke consumption are listed

Table 4. The economic titanium load.

Item	The lower limit [Ti], %	The maximum [Ti]/(TiO ₂)	(TiO ₂), %	The economic titanium load, kg/t
value	0.10	0.05	2	7.41

Table 5. The cost of raw material for protection.

Raw materials for protection	Mass, kg/t	Price, RMB/kg	P ₁ , RMB/t
Chengde titanium pellet	39	555	21.65
Imported titanium ore	28	673	18.84
Titanium ore	43	656	28.21

Table 6. The cost of flux consumption.

Raw materials for protection	Mass, kg/t	Price, RMB/kg	P ₂ , RMB/t
Chengde titanium pellet	2.18	277	0.60
Imported titanium ore	2.47	277	0.69
Titanium ore	2.84	277	0.79

Table 7. Saving the cost of molten iron.

Raw materials for protection	Mass, kg	Price, RMB/kg	P ₃ , RMB/t
Chengde titanium pellet	22.10	1 923	-42.50
Imported titanium ore	13.03	1 923	-25.06
Titanium ore	22.56	1 923	-43.38

Table 8. The cost of coke consumption.

Raw materials for protection	heat, kJ	Coke mass, kg/t	Price, RMB/kg	P ₄ , RMB/t
Chengde titanium pellet	831.16	29.63	1 717	50.88
Imported titanium ore	1 234.06	44.00	1 717	75.54
Titanium ore	1 568.83	55.93	1 717	96.03

Table 9. The total cost.

Raw materials for protection	Mass, kg/t	P, RMB/t
Chengde titanium pellet	39	30.63
Imported titanium ore	28	70.01
Titanium ore	43	81.65

in Tables 5, 6, 7 and 8, respectively. The total cost is summarized in Table 9, the economic order of raw materials for protection: Chengde titanium pellet > the imported titanium ore > the titanium ore.

The relationship between the fettling rate and the thermocouple temperature of a commercial BF is shown in Fig. 8. It can be concluded from Fig. 8, the protection effect was reflected by the fettling rate. The temperature increased rapidly when the fettling rate reduced, especially when the fettling rate was negative, the temperature reached the highest. While, the temperature decreased when the fettling rate remained above 30%.

4. Conclusions

In order to clarify the erosion mechanism of carbon brick

Fig. 8. The relationship between the fettling rate and the thermocouple temperature. (Online version in color.)

and realize the economical and efficient protection for blast furnace hearth at the end of the service, the damaged carbon bricks were analyzed, a model of economical and efficient protection for hearth was established, the following results were summarized:

(1) The carbon content of molten iron is undersaturated in hearth, the carbon undersaturation degree is related to the volume of BF, the carbon undersaturation degree of large BF is lower which may be the reason of long service life for large BF.

(2) The dissolution and the penetration were considered as the reasons for the erosion of carbon brick. The erosion of carbon brick can be divided into four processes, the four processes constitute a cycle which causes the erosion of carbon brick gradually.

(3) The economic evaluation was established based on the titanium content of molten iron, the distribution ratio of titanium, the composition of raw material, the price of raw material and the operation of BF, the model guides the selection of the economical protection raw material according to the evaluation.

(4) The fettling rate was defined as the evaluation index of the protection effect, the protection effect can be reflected by the fettling rate.

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