Prediction Model of Coke Strength after Gasification Reaction

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Mechanisms of the breakage and fines generation of cokes after gasification reaction were studied standing on the basic viewpoints as follows:
1) The coke is a compound of plural kinds of coke textures with respective strength and reactivity and both the strength and reactivity of coke in total are dominated by the coke textures composition and pore volume fraction.
2) The change in the strength after gasification reaction is caused by the change in the coke textures composition and pore volume fraction due to the gasification reaction.

According to the basic viewpoints, a mathematical model was developed which calculates the change in the coke textures composition and pore volume fraction during gasification reaction and predicts the strength of coke after gasification reaction.

Experiments were made on the gasification and size degradation of cokes using five kinds of coke samples with different coke textures composition and the model was confirmed useful to predict the reaction rates and the strengths after gasification reaction.

KEY WORDS: coke; gasification reaction; CRI (coke reactivity index); CSR (coke strength index after reaction); coke texture; pore; breakage contact model; coke gasification reaction model; coke fines generation model.

1. Introduction
Cokes are indispensable material in the blast furnace ironmaking process which form packed bed in the blast furnace lower part and sustains the flow passes of liquid metal and slag toward the hearth and of high temperature reducing gas toward the upper part of reducing and smelting zone. Therefore, severe control is being made on the strength of blast furnace cokes before and after gasification reaction. Such indices as drum index DI and coke strength after gasification reaction CSR are popularly used as mechanical strength indices. However, they are only the test results under limited conditions and don’t stand for the basic property to represent the breakage phenomenon of coke particles. Therefore, the establishment of the fundamental theory to contribute to the appropriate coke quality control has been desired.

Based on these backgrounds, the contact breakage model was proposed by authors and was confirmed authentic for the elucidation of the contact breakage phenomena of cokes both at the drum test system and simple shear test system. However, the previous study did not take into account the influence of the gasification reaction on the breakage of cokes. On the other hand, it is well known that cokes deteriorate their strength remarkably through gasification reaction in the actual blast furnaces. Therefore, it is inevitable to clarify and quantify the influence of gasification reaction on the breakage phenomenon of coke particles.

This study relates with the clarification of the mechanism of the breakage of coke particles after gasification reaction on the basis of the contact breakage model for coke particles. This study regards the coke as the compound of plural kinds of coke textures (optical textures) such as isotropic, mosaic, fibrous and inert with respective strength and reactivity. It is natural to think each coke texture has its own strength and reactivity because physical and chemical properties as well as optical property originate in the molecular structure and the coke textures are just the optical property of the respective molecular structures. Actually, the selective gasification reaction of highly reactive textures such as isotropic and inert was confirmed at the cokes sampled from the quenched furnaces. Pioneering trials to quantify the reactivity and strength of respective coke textures had already been made. However, there has been almost no following attempt to quantify the coke qualities on the basis of this viewpoint.

In this study, a mathematical model was developed. This model consists of two sub models as “coke gasification reaction model” and “coke fines generation model”. The role of the former model is to predict the change in the coke textures composition and pore volume fraction within coke particles during the gasification reaction. The role of the latter model is to predict the amount of fines generation from cokes after gasification reaction in several kinds of breakage systems such as drum test machines, the raceway and deadmen surface inside blast furnace. Experiments were made on the gasification reaction of coke particles and the fines genera-
2. Coke Gasification Reaction Model and Coke Fines Generation Model

2.1. Basic Viewpoint and Outline of the Model

Figure 1 shows the microscopic views of cokes before and after gasification reaction. The figures show both the cokes before and after gasification reaction are constituted of plural kinds of optical textures and pores. And the textures composition and pore volume fraction change from before to after the gasification reaction. Hereafter, the optical texture of coke is called “coke texture”. On the other hand, each coke texture has proper defects of its own. For example, the fusinite texture has the mesh like constitution involving small openings. Also other coke textures such as isotropic texture and mosaic textures have lattice defects like crystal boundaries within themselves. These openings are usually regarded as the same pore as is formed at the dilatation stage due to the removal of volatile matter. However, these openings are peculiar to the coke textures themselves and they are thought to be an important factor to dominate the strength and reactivity of respective coke textures. Here in this model, respective coke textures are regarded to have openings of their own in fixed volume fractions and these openings are discriminated from the pore to be formed at the removal of volatile matter.

The strength of the compound material includes pore depends on the strengths of respective textures composing material, their composition and the pore volume fraction. Actually, there are many kinds of practical formula to express the strength of compound material and porous material in the field of material science. Additionally, the reactivity of the compound material must depend on the reactivity of respective textures and their composition. Therefore, if the respective coke textures have the proper strength and reactivity of their own, both the strength and reactivity of any cokes can be predicted with using their coke textures compositions and pore volume fractions.

Above mentioned is the basic viewpoint of this study. There are many kinds of coke textures and therefore, it is favorable to classify them into several groups for the shake to save CPU time. In the model to be developed, the coke textures were grouped into following five kinds of coke textures as isotropic, mosaic, fibrous, leaflet and inertinite texture. Here, fine mosaic and coarser mosaic were not separated. Domain texture was classified as leaflet texture. Semi-fusinite, fusinite and micrinite were classified all together as inertinite texture.

Figure 2 shows the characteristics of the size degradation of cokes before and after gasification reaction at the CRI and CSR test system. The size distribution pattern in the right side figure shows the breakage mode is surface compressive breakage as was predicted by the previous work. Therefore, once the compressive strength of cokes is given, its breakage phenomena can be predicted with the help of the breakage contact model. On the other hand, the left side figure shows the steep decrease of the cumula-

Fig. 1. Microscopic view of coke constitution.

Fig. 2. Characteristics of coke size degradation at CRI and CSR test system.
tive over 9.5 mm at the early stage of revolution in the coke particles after reaction, which indicates the coke particle after gasification reaction has the strength distribution along radial direction within particles. This must be due to the radial distributions of coke textures composition and pore volume fraction. Therefore, it is inevitable to consider the distributions of coke textures and pore volume fraction in the radial direction within particle for the evaluation of the size degradation and fines generation of cokes after gasification reaction. In the mathematical model to be developed, the coke particles are assumed sphere with the radial distributions of coke textures composition and the pore volume fraction. At the calculation of the change in the radial distributions of coke textures composition and the pore volume fraction, the volume reaction model is adopted which considers the distribution of reaction rate along the radial direction by taking into account the effect of gaseous diffusion. At the calculation of the fines generation of cokes after gasification reaction, the compressive strength of cokes is regarded to change with the change in coke size due to the fines generation.

2.2. Coke Gasification Model

According to the volume reaction model, the changes in the coke textures composition and the pore volume fraction during gasification reaction are expressed by the following differential equations.

\[ \partial (e C g Y) / \partial t + \partial (J d + Y J f) / \partial r = \sum m_i R_i \] \hspace{1cm} (1)

\[ \partial (V_i C_i) / \partial t = \sum m_i R_i \] \hspace{1cm} (2)

Here, the first and second equations represent the mass balances of gas and coke respectively. As for nomenclature, suffix i represents the respective coke textures. Keys \( C_i \) and \( V_i \) are the molecular densities and the volume fractions of respective coke textures. As regards the gas, the key \( C_g \) is the molecular density. Suffix j is the number of gas components and the key \( Y_j \) is the volume fraction of respective components CO, CO\(_2\), and N\(_2\). The key \( e \) represents the pore volume fraction and is related with the volume fraction of coke textures by the next equation.

\[ e = 1 - \sum V_i \] \hspace{1cm} (3)

The key \( J d \) represents the diffusion flux of respective gas components and restricted by the Stephan Maxwell equations as follows:

\[ C_i \partial Y_j / \partial r = \sum (Y_j J d_j - Y_j J d) / De_{ij} \] \hspace{1cm} (4)

Here, next formula is adopted for the inter diffusion coefficients.

\[ De_{ij} = D_{ij} (e - e_0)^2 \] \hspace{1cm} (5)

The key \( e_0 \) is the volume fraction of closed pore and its value was set at 0.15 in this model. The key \( J f \) represents the flux of bulk gas flow and is restricted by the next equation which is derived by the summation of Eq. (1) under considering the relationship of \( \sum Y_j = 1 \).

\[ \partial J f / \partial r = \sum \sum m_j R_i \] \hspace{1cm} (6)

As regards the gasification reaction, the key \( R \) represents the gasification reaction rate of respective coke textures and the key \( m_j \) is the stoichiometric constants. Here in this model, the following formula by Turkdogan\(^1\) was adopted to express the reaction rate for all coke textures.

\[ R = C / k_1 P_g (Y_{CO_2} - Y_{CO_2}^0) / (1 + k_2 Y_{CO_2} / k_2) \] \hspace{1cm} (7)

Here, the key \( P_g \) represents gas pressure and \( Y_{CO_2}^0 \) is the equilibrium composition of CO\(_2\) for gasification reaction. Parameters \( k_1 \) and \( k_2 \) are the constants to express the reaction rate and the influence of the adsorption of CO on the reaction sites. The difference in reactivity among coke textures is expressed by the difference in the parameter \( k_1 \) among coke textures.

According to the experimental study by Takatani,\(^1\) the practical expressions of the rate constants are given as follows:

\[ k_1 = A_1 \exp (-27730 / T), \hspace{1cm} A_1 = 4 \times 10^5 \] \hspace{1cm} (8)

\[ k_2 = A_2 \exp (-15550 / T), \hspace{1cm} A_2 = 4 \times 10^5 \] \hspace{1cm} (9)

Tate\(^6\) confirmed it possible to express the difference in the reactivity among coke textures as the difference in rate constants among coke textures. Following to this result, the difference in the reaction rates among coke textures is expressed in this model as the difference in entropy terms \( A_1 \) of the reaction constant \( k_1 \).

As regards the integral of the differential Eqs. (1) and (2), the differential ranks of Eq. (1) are second for position \( r \) and first for time \( t \) and that of Eq. (2) are first for time \( t \). At the practical calculation, following conditions were set for gases and coke textures.

\[ Y_j (r = r_0) = Y_{j0} \] \hspace{1cm} (10)

\[ \partial Y_j / \partial r |_{r = 0} = 0 \] \hspace{1cm} (11)

\[ Y_j (t = 0) = Y_{j0} \] \hspace{1cm} (12)

\[ V_i (r = r_0) = V_i^0 \] \hspace{1cm} (13)

Here, the key \( r_0 \) represents the particle radius. The key \( Y_{j0} \) is the reducing gas compositions and the key \( V_i^0 \) is the volume fraction of coke textures before gasification reaction.

2.3. Coke Fines Generation Model

According to the contact breakage model,\(^1\) the strength to dominate the breakage of coke particle is compressive strength. Therefore, compressive strength must be expressed as a function of the constitution of coke before and after gasification reaction. The formula usually used to express the strength of porous material is as follows:

\[ S = S_0 \exp (-b e) \] \hspace{1cm} (14)

The key \( S_0 \) represents the strength of matrix and the key \( e \) is the pore volume fraction. The key \( b \) is the coefficient to quantify the effect of the pore volume fraction on the strength of porous material.

Nishio had confirmed the tensile strength of lump coke could be expressed using this formula.\(^7\) Here, the kind of strength to be considered in this model is not the tensile strength but the compressive strength. However, the compressive strength is supposed to be in proportion to the tensile strength. Therefore, the same formula is adoptable for
compressive strength. On the other hand, the strength of the compound material composed of plural textures with different strength is usually expressed as the volumetric average of the strengths of respective textures. On the basis of these understandings, following formula is adopted in this model for the expression of the compressive strength of lump coke.\[ S_c(r) = \sum V_i(r)S_{ci} \exp(-b \varepsilon(r)) \] (15) The key \( S_c \) represents the compressive strength of respective coke textures with proper values. Here, the compressive strength \( S_c \) is regarded to depend on the particle radius \( r \). Therefore, the keys \( S_c, V_i \) and \( \varepsilon \) are written as a function of \( r \) in this equation. Practical values for \( V_i(r) \) and \( \varepsilon(r) \) are given by the coke gasification model and the radial distribution of the compressive strength is calculated by the Eq. (15).

Once the compressive strength of coke particle is given as a function of particle radius, the amount and the rate of fines generation can be calculated according to the contact breakage model. In the case of normal static compression, the key \( P \) given, the maximum displacement \( \delta^* \) is calculated with using these equations and the fines generation ratio is calculated by the equation as follows:

\[ \Phi(x) = \frac{\int_0^{x_0} 2\pi x S_c(r') dx}{\int_0^{R} 4\pi r^2 \rho(r) dr} \] (19)

Here, the key \( P \) represents the compressive force and the key \( \delta^* \) is the contact displacement. Keys \( x, x_0 \) and \( r^* \) are the distance of the concerned point from the center of the contact plane, the radius of the contact plane and the distance of the concerned point from particle center. When the contact force \( P \) is given, the maximum displacement \( \delta^* \) is calculated with using these equations and the fines generation ratio is calculated by the equation as follows:

\[ \Phi(x) = \frac{\int_0^{x_0} 2\pi x \rho(r') dx}{\int_0^{R} 4\pi r^2 \rho(r) dr} \] (19)

Here, the key \( \rho(r) \) is the density of cokes at the point \( r \) and is given by the equation as follows:

\[ \rho(r) = \sum V_i(r) \rho_i \] (20)

Here, the key \( \rho_i \) represents the densities of respective coke textures and is set at 1.900 kg/m³ for all coke textures for a time in this model.

In the case of collision contacts such as drum tests and raceway, it can be assumed the collision contact occurs evenly the whole particle surface. Therefore, the rate of fines generation is expressed by the next equation.

\[ d\Phi(r)/dt = (1 - \Phi(r))\omega(E/M)_c \] (21)

\[ \Phi(x) = \frac{\int_0^{R} 4\pi r^2 \rho(r) dx}{\int_0^{R} 4\pi r^2 \rho(r) dr} \] (22)

Here, the key \( (E/M)_c \) represents the apparent fines generation energy at the point \( r \) from particle center. The parameter called “fines generation energy” was defined in the previous study as the amount of energy consumed to generate unit mass of fines and the parameter “apparent fines generation energy” was defined as the total energy supplied to generate unit mass of fines. Namely, the latter includes the restitution energy in addition to the purely consumed one. According to the contact breakage model, the value of the apparent fines generation energy is given as follows:

\[ (E/M)_c = (E/M)_{D_{p_{max}}}(2r/D_{p_{min}})^2 \gamma \] (23)

\[ (E/M)_{D_{p_{min}}} = 22,000(S_c/10^6)^0.45(D_p/10^{-3})^{-0.32}b^{-0.25} \] (24)

\[ \gamma = 3,400c_{i-0.3}(D_p/10^{-3})^{-0.75}v_{1.0}(S_c/10^6)^{-1.9} \] (25)

In the Eq. (23), the key \( (E/M)_{D_{p_{max}}} \) is the apparent fines generation energy for the size of \( D_{p_{max}} \) \( D_{p_{min}} \) is the size to discriminate finer fragments from coarser. The key \( \gamma \) is the power index to express the size distribution of coarser breakage fragments as the power function. In these equations, the key \( v \) is the collision velocity of cokes with other coke or with the drum wall. The key \( e_i \) represents the cumulative specific energy loaded on cokes. The key \( D_p \) is the initial size of cokes.

On the other hand, the key \( w \) represents the work rate loading on particle surface and is given as follows:

\[ w = (1/2)\tau^2 \] (26)

Here, the key \( \tau \) is the collision frequency. According to DEM calculation, the collision velocity and collision frequency are 5 m/s and 1.5 times per a rotation in the case of DI drum test and they are 2.8 m/s and 2 times per a rotation in the case of CSR drum test.

With using the equations above introduced, not only strength indices such as DI\textsubscript{150} and CSR but also the size degradation and fines generation rates at arbitrary breakage system can be evaluated.

**Figure 3** shows the relationship between compressive strength and size degradation for the cases of CSR and DI drum test conditions calculated by Eqs. (21) to (26). (The distribution of compressive strength within coke particle is not considered in these cases.) The compressive strength of coke before reaction is supposed around 45 MPa and the influence of the change in compressive strength on the size degradation is very small in this range. However, the coke strength deteriorates through the gasification reaction. This figure shows the influence of the coke strength becomes significant when the compressive strength deteriorates.

![Fig. 3. Relationship between compressive strength and cumulative oversize at drum tests.](image-url)
2.4. Setting of Reactivity and Strength for Respective Coke Textures

Tate made had evaluated the differences in the rate constant of gasification reaction among coke textures. Result obtained by Tate was adopted to determine the relative values of the entropy term of rate constants $A_i$, for respective coke textures as listed in Table 1. The absolute value for mosaic texture was fitted for the values of CRI calculated by this coke reaction model to agree in order with measured ones and the value obtained was $1.58 \text{ Pa}^{-1} \text{ sec}^{-1}$.

Nishioka et al. had studied on the influence of pore volume fraction on the tensile strength and decided the value $b$ equal 4.2. Here, the value $b$ for tensile strength is not the same as the value $b$ for compressive strength. Additionally, there may be some difference in the values $b$ between the original pore and the pore after introduced by gasification reaction. However, no precise data on this issue are available at present. On the other hand, the tensile strength and the compressive strength are supposed nearly in proportion to each other in case of the same kind of material. Then, if the compressive strength to tensile strength ratio is assumed constant in case of cokes, the values $b$ for tensile strength and compressive strength can be assumed the same. This model assumes the compressive strength to tensile strength ratio is constant before and after gasification reaction and sets the value $b$ for compressive strength at the same value as 4.2 obtained by Nishioka et al. for tensile strength.

Nishioka et al. had also studied on the micro strengths of respective coke textures and evaluated the respective values. However, the strength this model considers is not the micro strength but the compressive strength. The relative values of micro strengths for respective coke structures may correspond to those of compressive strengths because both the micro strength and compressive strength of texture are the strength of the matrix excluding pore. But, as a matter of fact, absolute values are completely different. Accordingly, the values were decided through the fitting procedure for the values $D_{15}$ of 1,200 numbers commercial cokes calculated by this model to correlate with the actual values. Results obtained are listed in Table 1 as the relative values to the mosaic textures. The absolute value for mosaic texture was fitted at 450 MPa. As shown in the table, mosaic and fibrous texture have relatively high values, which coincides with the results by former reports.

2.5. Examples of Models Calculation

Some examples are shown in this clause to make it clear the constitution of the coke gasification model and fines generation model introduced in the previous clauses.

Figure 4 shows an example of the calculation of coke gasification model for the CRI test condition. The reaction curve and the distributions of reaction parameters at the end of reaction are listed. According to the model, almost all the highly reactive textures are consumed and the volume fraction of pore becomes larger near the particle surface and as a result, compressive strength near the particle surface deteriorates significantly. However, as a result of gas diffusion, reaction extends deeply toward the particle center and accordingly, compressive strength inside particle also deteriorates.

Figure 5 shows the progressions of the size degradation of coke after reaction during I type drum test (CSR test) calculated by the calculation of fines generation model. Curves show the change in fine generation patterns with the increase of reaction time. This figure indicates that the size degradation speed is high at the early stage of rotation but gradually becomes lower in the same way as was shown in Fig. 2. This is because the strength degradation becomes slighter toward the particle surface as shown in the upper right side figure in Fig. 4.

Figure 6 shows two figures. One is the progression of

| Texture  | Isotropic | Inerinite | Mosaic | Fibrous | Leaflet |
|----------|-----------|-----------|--------|---------|---------|
| Reactivity $A_i/A_{i,\text{base}}$ | 10.0 | 4.0 | 1.0 (base) | 0.1 | 0.1 |
| Strength $S_c/S_{c,\text{base}}$ | 0.9 | 0.6 | 1.0 (base) | 1.1 | 0.4 |
coke size degradation on the compressive strength curves in respect to the increase of reaction time. The other is the relationship between reaction ratio and fines generation ratio. As the reaction progresses and expands towards the inside of particle with the increase of reaction time, the strength deterioration increases and expands toward the inside with the progress of reaction. Therefore, as shown in the right side figure, the size degradation increases with the increase of reaction ratio.

Figure 7 shows the breakage pattern of cokes before and after gasification under the static compression. The left side figure shows the relationship between compressive stress and contact displacement and the right side figure shows the relationship between fines generation and compressive stress under the static compression. These figures show both the displacement and fines generation ratio increase with the increase of reaction time, or in other words, with the increase of reaction ratio. On the other hand, each curve has a ending point. This point corresponds to the criteria of bulk breakage that is prescribed by the next equation.9)

\[ P_b/(\pi r^2) = S_t/0.7 \] ........................(27)

Here, the key \( P_b \) is the critical compression force for bulk breakage and the key \( S_t \) is the tensile strength. The tensile strength is set at \( S_t/8 \) in this calculation. As shown in the figures, the critical stress for bulk breakage also decreases with the increase of reaction ratio. However, if it is taken into account the compressive stress in the blast furnace lower part is estimated 1 MPa,13) the dominant breakage mode could be still regarded as the surface compressive breakage even after the gasification reaction.

3. Experiments on Coke Gasification and Strength Degradation

3.1. Experimental Method

1) Experimental Procedure

Five kinds of coke samples with different coke texture compositions were used for the experiments. They were manufactured using the electric heat furnace with the capacity of 50 kg coal per heat. Texture compositions and pore volume fraction of coke samples are listed in Table 2.

DI drum tests were made at first to confirm the strength of coke samples. Test conditions are on accordance with JIS standard used for the evaluation of the index DI15. Then, gasification reaction tests were made under the conditions as reaction temperature of 1 100°C, reaction gas of 100% CO\(_2\) and sample particle size of 20 mm. The reaction time was set at 1 and 2 h. The case with the reaction time of 2 h is just the same as CRI test. Additionally, reaction tests for
the reaction ratio to adjust 25% were made for all samples by fitting the reaction time. All the samples after reaction tests were tested by I-type drum with the tube length of 0.7 m and the changes in the weight fraction of +9.5 mm were measured. I-type drum used here has the standard legislated for CSR test. Therefore, the values of +9.5 mm weight fraction corresponding to 600 rotations for the coke samples after 2 h reaction test equal to the index CSR of respective coke samples.

### Table 2. Coke textures composition of coke samples.

| Case No. | 1 | 2 | 3 | 4 | 5 |
|----------|---|---|---|---|---|
| Isotropic | 20.1 | 18.0 | 12.2 | 7.6 | 25.3 |
| Mosaic | 38.2 | 30.7 | 34.6 | 28.3 | 38.5 |
| Fibrous | 12.1 | 8.9 | 18.0 | 32.0 | 5.1 |
| Leaflet | 2.0 | 5.7 | 0.9 | 3.4 | 1.0 |
| Semifusite | 17.9 | 26.4 | 23.0 | 18.3 | 21.4 |
| Inertinite | 9.8 | 10.4 | 11.4 | 10.4 | 8.8 |
| Pore | 48.0 | 47.5 | 48.0 | 47.5 | 48.2 |

### Table 3. Qualities of coke samples.

| Sample No. | DI15 | CRI | CSR |
|------------|------|-----|-----|
| 1 | 81.5 | 37.6 | 45.8 |
| 2 | 74.1 | 41.0 | 30.4 |
| 3 | 80.8 | 38.0 | 43.0 |
| 4 | 82.3 | 29.1 | 59.6 |
| 5 | 80.6 | 44.4 | 34.4 |

### 3.2. Experimental Results

1) Relations between Coke Qualities and Coke Textures

Table 3 lists the coke quality indices measured for each coke sample. Figure 8 compares the coke strength index DI15 and the coke reactivity index CRI with coke textures compositions. As shown in the figure, the strength index DI15 corresponds to the amount of the space fractions with high strength textures and the reactivity index CRI agrees with the amount of the space fractions with high reactivity textures. These correspondences imply the basic viewpoint this study stands on is acceptable.

2) Comparison of DI15, CRI and CSR Measured and Calculated

Figure 9 compares the reaction ratios for each coke sample measured with the reaction curves calculated for each coke sample. The coke gasification model explains well the measured reaction ratios.

Figure 10 shows the size degradation profiles of each coke sample after 2 h reaction at I type drum tests measured and calculated. The fines generation model also elucidates well the size degradation profiles for each coke sample after reaction.

Figure 11 summarize the correlations of indices DI15, CRI and CSR measured and calculated. According to these results, the model explains both the reactivity and strength after reaction, which confirms the authenticity of the basic viewpoints this study stands on. Namely, the coke is supposed to be the compound of coke textures with respective

![Fig. 8. Relations between coke textures composition and coke qualities.](image1)

![Fig. 9. Gasification reaction profile measured and calculated.](image2)

![Fig. 10. Size degradation profile of coke after reaction measured and calculated.](image3)
strength and reactivity of their own and the physical as well as chemical properties of coke are dominated by the coke texture compositions and the pore volume fraction.

4. Discussions

4.1. Influence of Coke Reactivity on Coke Strength after Reaction

The prediction model of coke strength after gasification reaction has been developed and was confirmed authentic. According to the model, both the reactivity and strength before and after the reaction depend on the coke textures composition and pore volume fraction and the change in the strength after reaction is due to the change in the coke textures composition and pore volume fraction through the reaction. Therefore, there must be strong relationship between reaction ratio and strength after reaction.

Figure 12 shows the relationships between reaction ratio and strength after reaction. The figure confirms the strong relationship between reaction ratio and strength after reaction. However, this figure also shows respective curves are discriminated by the initial strength before reaction in spite that there are big differences in coke textures compositions and reactivity among five coke samples.

Figure 13 shows the apparent fine generation energy profile in respect to particle radius. The values of apparent fines generation energies plotted in the figures were evaluated using the experimental data considering the Eqs. (21) and (22). The relative radius $R/R_0$ was set equal to CSR$^{1/3}$ under supposing the breakage mode at I type drum is surface compressive breakage and the shape of the residual coke particles after degradation is in symmetric with the original ones. Each dot corresponds to the rotation times at 100, 200, 400, 600 and 800 from right to left within the figures. The left side figure corresponds to the case with the reaction time of 2 h. This figure shows that the apparent fines generation energies for the cokes with high reactivity are lower than those of cokes with low reactivity, which agree with the fact that the value of CSR of the cokes with low reactivity is high. However, in the case when the reaction ratios were set equal, the strength deterioration of the cokes with high reactivity must be lower. This is because the gasification reaction becomes partial to the particle surface and the strength inside particle is expected less suffered from gasification reaction. The right side figure corresponds to the cases with the reaction ratio of 25%. The inclines for respective plots indicate the strength deterioration pattern towards the inside of particle. As is shown by the difference of the inclines for respective cokes and the shape of the residual coke particles after degradation is in symmetric with the original ones. Each dot corresponds to the samples No. 4 and 5, the breakage finishes before the compressive strength of high reactivity coke becomes greater than that of initially high strength coke. Figure 14 shows the size degradation profiles of respective coke samples at the same reaction ratio of 25%. The gradient along the rotation time seems a little steeper in No. 4 coke. However, this effect is too small for its size degradation ratio to outrun other coke samples. As a result of these discussions, it can be said the strength after reaction qualified by the index CSR is dominated by two factors as the reactivity and the strength before reaction.

The reaction temperature must affect strongly on the reactivity of cokes and is supposed to change the strength deterioration profile within coke particle. Figure 15 shows the calculation results on the influence of temperature on the coke size degradation. In the calculations, the mechanical load condition was set at the same condition as CSR test. According to the calculations, the size degradation decreases with the increase of reaction temperature. This is due to the increase of surface reaction. However, the effect is limited within the reaction ratio of higher than 15% and the reaction temperature of higher than 1400°C. According to this model, it can be said the influence of reaction temperature on the size degradation is not so significant when the reaction temperature is lower than 1400°C.
4.2. Estimation of Fines Generation inside Blast Furnace

The model can also estimate the size degradation of cokes inside blast furnace if the mechanical load condition cokes are to suffer from is given. The most severe parts for coke degradation inside blast furnace are raceway and deadman. Figure 16 shows the estimation of the relationships between the gasification reaction ratio and the fines generation ratio at those two parts in respect to reaction temperature. Here, the particle size was set at 50 mm and the fines size is set at under 3 mm. Respective mechanical load conditions were evaluated on the basis of previous studies\textsuperscript{13,14)} as the 5 times of collisions at 10 m/s speed for raceway and the one cycle of slipping distance under the compression of 1 MPa for deadman surface. The properties of cokes adopted are those of No. 1 coke sample.

The figures show that the size degradation becomes severe with the increase of reaction ratio. In case of deadman, the fines ratio is larger when reaction temperature is high. But this tendency is in the region the reaction ratio is less than 30% and when the reaction ratio exceeds 30%, the fines ratio for high reaction temperature becomes lower. In case of raceway, fines ratio increases with the increase of reaction ratio and the effect of reaction temperature is small until the reaction ratio is less than 15%. However, the reaction ratio exceeds 15%, the effect of reaction temperature becomes significant and the fines ratio becomes higher with the decrease of reaction temperature. These differences depend both on the difference in mechanical load conditions and on the strength deterioration profiles which change with reaction temperature. According to the results, the fines ratio in raceway is 10 times higher than that of deadman. Even if the oxygen in hot blast consumes most of them, some parts will escape from the combustion and accumulate somewhere in the blast furnace lower part. On the other hand, since the oxidizing gas components are scarce near deadman surface, most of fines generated near there will remain unconsumed. Therefore, both of them are regarded as the principal fines site.
5. Conclusion

The prediction model of coke strength after gasification reaction has been developed. The model stands on the basic viewpoint that the coke is the compound of coke textures and pore and the coke properties are dominated by the coke textures composition and pore volume fraction.

Experimental study was made on the reactivity and the strength of cokes after gasification reaction and the model was confirmed authentic through the experiments.

According to the model and experiments, both the strength and reactivity of cokes before and after gasification reaction are dominated by the coke textures composition and pore fraction. Therefore, how to compose the appropriate coke textures is the inevitable viewpoint at the appropriate coke quality control.

REFERENCES

1) H. Kimura and T. Miyazu: Tetsu-to-Hagané, 58 (1972), No. 1, 158.
2) Y. Okuyama, T. Miyazu, H. Sugimura and M. Kumagai: J. Fuel Soc. Jpn., 49 (1970), No. 522, 736.
3) H. Sugimura, M. Kumagai and H. Kimura: J. Fuel Soc. Jpn., 49 (1970), No. 522, 744.
4) H. Kimura, Y. Sanada, S. Sugawara, T. Furuta, H. Sugimura and M. Kumagai: J. Fuel Soc. Jpn., 49 (1970), No. 522, 752.
5) K. Kojima, T. Nishi, T. Yamaguchi and H. Nakama and S. Ida: Tetsu-to-Hagané, 62 (1976), No. 5, 110.
6) M. Tate: Report of Committee on the basic properties of coking coal, ISIJ, Tokyo, (1982), 97.
7) K. Nishiooka and S. Yoshida: Tetsu-to-Hagané, 70 (1984), No. 3, 343.
8) K. Nishiooka and S. Yoshida: Tetsu-to-Hagané, 70 (1984), No. 3, 351.
9) H. Yamaoka and K. Nakano: ISIJ Int., 43 (2003), No. 1, 36.
10) H. Yamaoka, S. Suyama and K. Nakano: ISIJ Int., 43 (2003), No. 1, 44.
11) E. T. Turkdogan and J. V. Vinters: Carbon, 8 (1970), 39.
12) K. Takatani and Y. Iwanaga: Tetsu-to-Hagané, 75 (1989), No. 4, 594.
13) K. Katayama, S. Wakabayashi, T. Inada, K. Takatani and H. Yamaoka: Tetsu-to-Hagané, 83 (1997), No. 2, 91.
14) H. Yamaoka and K. Nakano: Tetsu-to-Hagané, 86 (2000), No. 11, 733.