A Theoretical Model for the Contact Phenomenon of Coke Particle Accompanied by the Compressive Breakage at the Contact Plane

Hideyuki YAMAOKA and Kaoru NAKANO


(Received on June 26, 2002; accepted in final form on August 12, 2002)

This study considers the mechanism of the breakage contact of coke particles. A theoretical model has been developed standing on the hypotheses as follows:

1. The breakage mode of coke particle is the surface compressive breakage.
2. The Hertzian stress distribution is induced on the contact plane of particle surface but the region with the Hertzian stress over than the compressive strength makes contact breakage and the stress on this region reduces to the value equal to the compressive strength.
3. The energy to be consumed during breakage contact is equal to the energy to be consumed for producing breakage fragments (fines) and is in proportion to the mass of fines.

On the basis of these hypotheses, the relationship between contact force and contact displacement was formulated and additionally, the breakage volume, the consumed energy, the restitution coefficient or the friction coefficient at normal, rotating and slipping contact were expressed as a function of contact force and coke mechanical properties.

Particle dropping tests and simple shear tests were performed to check the authenticity of the breakage contact model and the impact forces measured at the particle dropping tests, the friction coefficient as well as the mass of generated fines at the simple shear tests were confirmed well agree with the values predicted by the model.

KEY WORDS: blast furnace; blast furnace lower part; coke quality; coke size degradation; coke fines generation; DEM; breakage contact; contact force; restitution coefficient; friction coefficient.

1. Introduction

Coke is an indispensable staff in blast furnace process, which forms packed bed in the blast furnace lower part and sustains the flow pass of liquid metal and slag downward to the hearth and of high temperature reducing gas upward to the reduction and smelting zone of blast furnace. Therefore, how to keep the packed bed structure of cokes appropriate for gas and liquid to flow stably is the biggest issue in the blast furnace operation and therefore, coke quality, burden distribution and blasting conditions are severely checked. However, the mechanism of the formation of coke packed bed in the blast furnace lower part or the quantitative effects of coke quality, burden distribution or blasting conditions on the structure of coke packed bed haven’t been clarified yet. This is due to the lack of the basic theory to elucidate the dynamics of coke packed bed.

There are two big items to be cleared concerning with the dynamics of coke packed bed. One is the mechanism of the movement of coke packed bed as particle assembly and especially, the mechanism of irregular movements such as channeling and hanging. Another one is the mechanism of the coke size degradation and the formation of coke fines from coke packed bed.

As regards the first problem, the packed bed of granular materials is often regarded as a continuous substance and the fluid dynamics or solid dynamics are adopted for the analysis of its movement. However, these methods could not elucidate the mechanism of the formations of raceway, channeling or hanging in spite that these phenomena indeed characterize the dynamics of coke packed bed in the blast furnace lower part. The particles packed bed is principally the ensemble of discrete particles and its movement is the appearance of the movements of discrete particles under the mechanical interactions with near by particles. Recently, a numerical model called DEM (discrete element method) has been developed by P. A. Cundall which considers the momentum equations for every particles to predict the movement of particles assembly. DEM method becomes widely used in the field of powders technology and it seems a promising method also for the prediction of the coke packed bed in the blast furnace lower part. In DEM model, the traction force due to the contact of particles must be expressed as a function of contact displacement. Usually, the Voigt Kelvin model is adopted for the expression of the traction force. But coke is not a viscid material
but a brittle material. Therefore, it seems difficult to adopt Voigt Kelvin model for coke particle. Some studies were made on how to express the traction force for actual materials considering the effect of the yielding of contact point but there is no model at present to express the traction force for brittle particle like cookes. Therefore, a new model to express the traction force for coke particle must be developed if DEM method is to be used for the prediction of the behavior of coke packed bed in the blast furnace lower part.

As regards the second problem, many kinds of indices such as drum index (DI) and tumbler index (TI) are practically used for the control of the mechanical quality of cookes. However, there is no theory to combine these indices with the coke size degradation or fine cokes generation in the actual blast furnace. Here, such phenomena as coke size degradation and coke fines generation are considered to occur due to the contact breakage of coke particle with other coke particles or with other object like furnace wall. Therefore, the key point to solve the problem is to clarify the mechanism of the contact breakage of coke particles. And if based on this viewpoint, the formulation of the traction force appropriate for cokes and the clarification of the mechanism of the contact breakage of coke particle are the same issue.

Standing on the viewpoint above mentioned, studies were made to develop the model to elucidate the breakage contact phenomenon of coke particles.

2. Development of the Breakage Contact Model

2.1. Mode of the Breakage of Coke Particle under Compression

The item to be cleared before the development of breakage contact model is the contact breakage mode of coke particle. There are two modes in the contact breakage of coke particle. One is the compressive breakage of contact plane and the other is the tensile breakage of particle itself. The critical forces of these two kinds breakage modes are evaluated as follows:

1) Critical Force for Surface Compressive Breakage

According to the Hertzian contact theory, the compressive force induced on the contact plane \( P_c \) is written in Eq. (1) as a function of equivalent Young's modulus \( Y = Y_1 + Y_2 \) (\( Y_1, Y_2 \)), equivalent particle radius \( r = r_1 r_2 / (r_1 + r_2) \) and the plane center displacement \( \delta_p = \delta_{p1} + \delta_{p2} \).

\[
P_c = \frac{4}{3} \pi^2 \delta_{p1} + \delta_{p2} 
\]

(1)

Here, the plane center displacement \( \delta_p \) means the displacement of the contact center point from the start to the completion of contact and is a half as large as the total displacement defined as the change in particle centers distance.

The compressive stress distribution formed on the contact plane is expressed by the Eq. (2).

\[
\sigma(x) = 3P_c / 2 \pi R(1 - x^2 / R^2), \quad R = (2r \delta_p)^{0.5} 
\]

(2)

Here, \( \sigma(x) \) is the stress on the point \( x \) apart from the plane center and \( R \) is the radius of contact plane.

In the case when maximum compressive stress becomes larger than the compressive strength of coke \( S_c \), the surface breakage should occur. In the case when a particle is pressed by a rigid plat (without curvature), both the equivalent radius and the equivalent Young's modulus equal to those of particle itself. Therefore, the critical force for surface breakage \( P_c \) is expressed as follows:

\[
P_c = \pi r^3 S_c \left( \pi^2 / 6 \right) (S_c / Y)^2 
\]

(3)

2) Critical Force for Bulk Tensile Breakage

As regards the bulk tensile breakage, the relationship between critical force \( P_t \) and tensile strength \( S_t \) is expressed as follows:

\[
P_t = \pi r^3 S_t / 0.7 
\]

(4)

3) Breakage Mode of Coke Particle under Compressive Force

Dividing Eq. (3) by Eq. (4), the ratio of two critical forces for surface compressive breakage and for bulk tensile breakage is given.

\[
P_c / P_t = (0.7 \pi^2 / 6) (S_c / S_t) (S_c / Y)^2 
\]

(5)

In the case of coke, the compressive strength to Young's modulus ratio \( S_c / Y \) has the order of 0.01 and the compressive strength to tensile strength ratio \( S_t / S_c \) has the order of 10. Therefore, the critical force for surface compressive breakage is far smaller than the critical force for bulk tensile strength. Therefore, the dominant breakage mode of coke particle under compression is judged the surface compressive breakage.

2.2. Fines Generation Energy

The breakage of material should be accompanied by the energy consumption. Generally, cracks are generated when induced strain exceeds its limit and energy is consumed for the sake to generate the cracks. However, some of generated cracks restore themselves and thermal energy is generated at this moment. In the case of ductile material, almost all the generated cracks restore themselves and as a result, object is deformed and all the consumed energy turns into thermal energy. On the other hand, in the case of brittle material, the restoration of cracks is negligible and as a result, fragments are generated and the consumed energy turns into the surface energy of the fragments. Here, coke is a brittle material. Therefore, in this study, it is assumed that all the cracks turn into surface energy of fragments (fines).

Focused on the contact plane under surface compressive breakage, the region with the compressive stress larger than the compressive strength is broken into fines and the compressive stress on this region becomes equal to the compressive strength itself. Especially in the case of rigid body, whole the contact plane is breakage region during the progress of breakage and the stress on the contact plane is kept equal to the compressive strength. Therefore, the energy consumption \( E_s \) is written as follows:

\[
E_s = S_c \int_0^\infty A(\delta) d\delta 
\]

(6)

Here, \( S_c \) is the compressive strength. \( A(\delta) \) is the area of contact plane at the displacement of \( \delta \).

On the other hand, the mass of fines \( M \) is written as follows:
Here, $\rho$ is the density. Key $k$ is the parameter to show the ratio of the broken volume to the swept off volume $v = \int_0^\delta A(\delta) d\delta$.

These two equations are in common to include swept off volume. Therefore, dividing Eq. (6) by Eq. (7), the following relationship is obtained.

$$\frac{E_i}{M} = \frac{S_c}{(kp)} \quad \text{(8)}$$

The Eq. (8) shows that the energy necessary to generate unit mass of fines is in proportion to the compressive strength to density ratio of the objective material. The value of $k$ is considered to change with the change of compressive conditions such as compression speed. However, if the range of the change in compression conditions is not so wide, $k$ is assumed constant and the value of $\frac{E_i}{M}$ is supposed to depend only on the mechanical properties of particle free from compression conditions. Accordingly, the parameter $\frac{E_i}{M}$ is so important at the discussion on the compressive breakage phenomena that it is called “fines generation energy” in this study.

### 2.3. Relationship between Force and Displacement at the Breakage Contact

As proved in clause 2.1, the dominant mode of the contact breakage of coke particle is surface compressive breakage. In this clause, the relationship between contact force and contact displacement at the contact accompanied by surface compressive breakage is derived.

The stress on the contact surface must be considered at the derivation of the relationship between contact force and contact displacement. On the other hand, the coke is a porous material with small concaves and convexes on its surface and therefore, the actual contact of coke particle is an assembly of contacts of convexes on the apparent contact plane. Therefore, it is difficult to evaluate the real stresses on the real contact points. However, the stress can be regarded practically as the ratio of the sum of forces loading on the real contact points within the concerned apparent contact plane to the area of this apparent contact plane. In the derivation of the relationship between contact force and contact displacement, the practical stress above explained is called “stress”. In other words, the surface is assumed completely flat.

According to the Hertzian contact theory, the relationship between contact force and contact displacement is expressed by Eq. (1). However, it is valid only in the case without accompanied by yielding or breakage. Here in this model, as shown in Fig. 1, following hypotheses are introduced.

1. The region within the contact plane where the normal stress exceed the compressive strength of particle matrix $S_c$ makes compressive breakage and the stress on the circulate region with the radius of $R_p$ drops to the value equal to the compressive strength itself.
2. The contact force at the stage $P_y$ is equal to the integral of the stress over the contact plane and balances with the elastic force $P_e$ induced in the faultless part of the particle.

The contact force at the stage $P_y$ is the key $P_y$ to balance the contact force $P_p$ could be expressed by the same formula as the Hertzian contact force.

Based on the hypotheses 1 and 2, following expression is obtained between normalized contact force $P_p/P_y$ and normalized plane center displacement $\delta_y$.

$$P_p/P_y = (\delta_p/\delta_y)^{1.5} \quad \text{for} \quad \delta_y < \delta_p$$

$$P_p/P_y = 1 + 1.5(\delta_y/\delta_p) \quad \text{for} \quad \delta_y > \delta_p \quad \text{(9)}$$

Here, $P_y$ is the critical contact force for surface compressive breakage. Keys $\delta_p$ and $\delta_y$ are the breakage displacement and the critical plane center displacement, respectively. Values of $\delta_p$ and $P_y$ are given as functions of compressive strength and Young’s modulus.

$$P_y = (4\pi/3)r\delta_p S_c \quad \text{(11)}$$

$$\delta_y = [(r/2)(\pi/2)^2(S_c/Y)^2 \quad \text{(12)}$$

The Eq. (9) relates the contact force with the plane center displacement. However, it is necessary to make it clear the relationship between contact force and total displacement for the purpose to evaluate the contact energy. In the case of elastic contact, the total displacement is equal to the double of the plane center displacement as mentioned in clause 2.1. However, in the case of breakage contact, this relation isn’t sustained. According to the hypotheses drawn in Fig. 1, the relationship among displacements is as follows:

$$\Delta_e = \Delta_x + \delta_p - \delta_y \quad \text{(13)}$$

Here, the key $\Delta_e$ is the elastic displacement to be induced in faultless part of particle and according to the hypotheses 2 and $\Phi$, it is restricted by the next equations.

$$P_p = P_e = (4/3)\rho^*Y_{\Delta e}^{1.5} \quad \text{(14)}$$

$$r\Delta_e = 2r\delta_p \quad \text{(15)}$$

The key $r_e$ is the apparent curvature radius of faultless part and is restricted by Eq. (15) because the radius of contact plane given by $\Delta_e$ should equal to the value given by $\delta_p$.

By combining equations from (9) to (15), the forward contact force $P_p$ is expressed as a function of total displacement $\Delta_e$ as follows:

$$P_p/P_y = 1 + 1.5[(\Delta_e/\delta_y + 17/4)^{1.5} - 1.5]^2 - 1 \quad \text{(16)}$$
In the case of backward contact, the broken part has no elasticity. Therefore, the only force that works during backward contact is the elastic force from the faultless part and when the contact is finished, residual displacement is left behind. Accordingly, the backward contact force \( P_y \) and the residual displacement \( \delta_y^* \) are given in the forms as follows:

\[
P_y = (P/P_y) \frac{\Delta_y - \delta_y^*}{\delta_y} \frac{1}{(\Delta_y^* - \delta_y^* - \delta_y^*)^{1/5}}
\]

\[
\delta_y^* = P_y - \delta_y
\]

Here, \( \Delta_y^* \), \( P_y \) and \( \delta_y^* \) are the maximum values attained during the forward contact.

The relationship between normalized contact force and normalized total displacement is shown in Fig. 2. The figure marks hysteresis. The area surrounded by two curves is corresponding to the energy to be consumed during the breakage contact. Here, the contact energy \( E \) is given by the integral of forward contact force over the total displacement, as follows:

\[
E = \pi r S_t \delta_y^2 \{16/15 + (X - 1)(X + 1/3) + 2X^{-4/3}(X^2 - 4X^{10/3} + 1/3)\}
\]

Here, \( X \) is the normalized plane center displacement defined as follows:

\[
X = \frac{\delta_y}{\delta_y^*}
\]

This value is connected with the normalized contact force by Eq. (9). From now on, \( X \) is used instead of \( \delta_y^* \) and \( P_y \) for the purpose to simplify the shape of equation.

On the other hand, according to the relationship between fines generation and energy consumption explained in clause 2.2, the consumed energy is given as the product of the mass of fines \( M \) and fines generation energy \( (E_c/M) \). The mass of fines is given as follows:

\[
M = \pi r S_t \delta_y^2 (X - 1)^2 pk
\]

Therefore, the energy consumption is expressed by the next formula.

\[
E_c = M(E_c/M) = \pi r S_t \delta_y^2 (X - 1)^2
\]

Based on the Eqs. (19) and (22), restitution coefficient \( \eta \) is obtained. The approximate form is given as follows:

\[
\eta^2 = (E - E_c)/E
\]

\[
\eta = 2/\sqrt{2} = 2/\left[2(P/P_y)^{3/2} + 1\right]^{1/5} + 1]
\]

Restitution coefficient is also shown in Fig. 2 as a function of \( P_y/P_y \). The restitution coefficient was usually assumed constant. However, according to the breakage contact model, it depends on the contact force. This is due to the effect of surface compressive breakage. As is known by Fig. 1, the ratio of residual displacement to total displacement increases with the increase of plane center displacement, which results in the decrease of restitution coefficient with the increase in contact force.

### 2.4. Parameters Characterizing Breakage Contact Phenomenon

There are three kinds of contact modes as normal, slipping and rotating contact. Here in this clause, parameters characterizing breakage contact phenomena such as fines generation, energy consumption, restitution or friction coefficient are derived for each contact mode.

In case of the particle with flat surface pane, breakage occurs only at the region where the Hertzian stress exceeds the compressive strength, as was discussed in clause 2.3. However, the roughness of the particle surface must be taken into account at the evaluation of the mass of fines generation and the amount of energy consumption.

The roughness of coke surface originates in the pores opening on the surface and most of the small convexes on the surface is the edges of honeycomb like wall exposing on the surface. The compressive strength of small convex is higher than that of particle itself because convexes are free from pores. However, most of convexes could be regarded small enough for the compressive stress to exceed their strength limits. Therefore, in this model, all the convexes compressed during the contact are assumed to be broken.

Based on these assumptions, the mass of fines to be generated and the amount of energy to be consumed during the contact are evaluated.

Figure 3 summarizes the outline to evaluate the mass of fines generation and the amount of energy consumption for the case of normal contact. The apparent contact area is given in the same way as the case of flat surface particle \( A_p = 2\pi r \delta_y^* \). But it is not the real contact area. The real contact area \( A_r \) equal to the total cross sections of broken convexes is given as the ratio of compressive force \( P_r \) to the compressive strength of convex \( S_{cm} \). The broken height of convex \( d \) is supposed to be nearly equal to the critical plane center displacement. Then, the mass of fines from convexes is given as the product of three items as the real contact area, the broken height and the density of convex. As discussed in clause 2.2, in the case of brittle material, the ener-
gy to be consumed through the compressive breakage is proportional to the mass of generated fines and the proportional constant equals to fines generation energy. Here in the model, this hypothesis is regarded still useful in the breakage of convex and fines generation energy for convex is considered to be given in the same form as Eq. (8). Followed by this assumption, the energy consumption is given as the product of two items as the mass of fines and fines generation energy for convex.

On the other hand, the mass of fines generated and the amount of energy consumed due to the breakage of particle itself must be taken into account when the plane center displacement exceeds its critical value. They were given by Eqs. (21) and (22). By adding these two terms respectively, the total mass of generated fines and the total amount of consumed energy are decided. The fines generation energy in total is given as the ratio of these two items.

\[ M_e = \frac{(4\pi/3)\sigma r^2 \rho \xi}{k} \quad \text{for } \delta_p < \delta_y \]

\[ E_m = \frac{\pi \delta^5 k (X - 1)^2 + 2(X - 1/3)}{k} \quad \text{for } \delta_p > \delta_y \]  

(24)

(25)

Here, \( n \) is the suffix to represent normal contact. \( M_{cm} \) and \( \rho_m \) are the compressive strength and the density of convex.

Restriction coefficient of this case is written in the form as follows:

\[ n = 16(15)(X^2 + X^{1.5}) + 2(X - 1/3) \]

(28)

The breakage of convexes occurs even in the case of contact force less than critical value. Therefore, restitution coefficient becomes lower in comparison with the case of flat surface particle.

Next is the derivation of parameters for the breakage during rotating and slipping contact. The relationship between contact force and contact displacement obtained for the case of normal contact is still useful in cases of slipping and rotating contacts. However, the contact plane is continuously renewed in these cases. Therefore, both the fines generation and the energy consumption increase with the increase of slipping and rotating distance. On the other hand, the energy consumption should be equal to the product of the friction force and the slipping and rotating distance. Therefore, if the mass of fines to be generated is given for certain slipping or rotating distances, both the energy consumption and the friction force are evaluated.

Such situations are imagined as two particles are contacting with each other and one of them makes a cycle of rotation (2\( \pi \)) with or without revolving movement. Another particle is reposing still. The case with the revolving movement at the same rate as cyclic rotation corresponds to the rotating contact and the case without revolving movement corresponds to the slipping contact. In these cases, a circular trace with the width of \((2r\delta_p)^{1/2}\) and a circular cave with the width of \((2r\delta_p)^{1/2}\) will be marked on the surface of rotating particle corresponding to the breakage of convexes and the breakage of particle itself, respectively. The trace and cave with the same widths will be marked on the other reposing particle surface in the case of rotating contact. On the other hand, a spherical trace with the radius of \((2r\delta_p)^{1/2}\) and a dimple with the radius of \((2r\delta_p)^{1/2}\) will be marked in the case of slipping contact.

As regards the mass of broken convex, the real contact area \( A_c \) to apparent contact area \( A_r \) ratio is approximately the same as that of normal contact (\( \alpha = A_c/A_r \)). Therefore, the total cross sections of broken convexes is given as the product of the area of circular trace and \( \alpha \). The broken height of convex at the rotating contact is given in the same way as at the normal contact because no shear stress works in both cases. However in the case of slipping contact, shear stress is induced on the contact plane and therefore, the height of broken convex isn’t equal to that of normal contact. In this case, if such case is imagined as two convexes compress their bodies to each other due to the shearing displacement, the height of convexes to be broken is regarded approximately equal to the height of convex itself. As regards the mass of fines generation due to the breakage of particle itself, the broken part is the circular cave of arc with the width of \((2r\delta_p)^{1/2}\).

Based on the above discussions, the mass of fines generation from convexes and particle itself, the total energy consumptions and the fines generation energy are expressed as functions of plane contact displacement.

\[ M_e = \frac{(8\pi/3)(2r\delta_p)^{1/2}X^2 \rho \xi}{k} \quad \text{for } \delta_p < \delta_y \]

\[ E_m = \frac{(8\pi/3)(2r\delta_p)^{1/2} X^{0.5} \xi}{k} \quad \text{for } \delta_p > \delta_y \]

\[ (E/M)_n = \frac{(S_n/kp_m)}{(X - 1)^2 + 2(X - 1/3)k} \quad \text{for } \delta_p > \delta_y \]

\[ \xi = \frac{(S_n/kp_m)}{S_n/k} (2) \]

(27)

(29)

(30)

(31)

(32)

(33)

(34)

(35)

Here, suffixes \( r \) and \( s \) represent rotating and slipping con-
Friction forces for rotating and slipping contact are given as the divisions of energy consumptions by distances of rotating and slipping. On the other hand, the contact forces are given by Eq. (9) for both cases. Therefore, the friction coefficients for rotating contact $m_r$ and slipping contacts $m_s$ are expressed as follows:

$$m_r = \frac{2}{p \partial \gamma} \left( \frac{d}{r} \right)^{0.5} \left( \frac{X}{H} \right)^{0.5}$$

for $d < \delta_p$, and

$$m_s = \frac{1}{p \partial \gamma} \left( \frac{d}{r} \right)^{0.5} \left( \frac{X}{H} \right)^{0.5}$$

for $d > \delta_p$. ....(36)

Fines generation energy, restitution coefficient and friction coefficient are drawn in Figs. 4 and 5 in respect to the normalized contact force. Here in the figures, $P_p$ is the contact force itself and $P_\gamma$ is the critical contact force determined by mechanical properties such as $r$, $S$, and $Y$. Therefore, all the parameters characterizing the breakage contact phenomena depend not only on the mechanical properties of cokes but also on the contact force load on particle.

3. Verification of the Breakage Contact Model

3.1. Collision Impact Force at Particle Dropping Test

As shown in Fig. 2, the model can predict the impact force to be induced at the collision of particle. In this figure, the collision energy corresponds to the integration of the forward contact force along the total displacement and the maximum impact force corresponds to the maximum contact force. In order to confirm the usefulness of the model for the impact force at the collision of particle, a dropping test was performed.

Three kinds of particles were prepared as shown in Table 1. These particles were dropped from several heights and the impact force was measured with using piezoelectric device.

Examples of the impact force profile are shown in Fig. 6. The first mounds of respective force curves correspond to the impact force profiles and the following curves show the oscillation of the plate itself. DEM calculations were made for each dropping tests using the traction force expressed by Eqs. (16) and (17). Calculation results for the cases with the dropping height of 4 m are shown in Fig. 7. Not only the intensities of impact force but also the intervals of the contact calculated agree well with those measured. All the

<table>
<thead>
<tr>
<th>Table 1. Materials used for particle dropping test.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Y (GPa)</td>
</tr>
<tr>
<td>S (GPa)</td>
</tr>
<tr>
<td>m (g)</td>
</tr>
<tr>
<td>r (mm)</td>
</tr>
<tr>
<td>ρ (kg/m³)</td>
</tr>
<tr>
<td>Yo (GPa)</td>
</tr>
<tr>
<td>Sv (GPa)</td>
</tr>
<tr>
<td>Vy (m/s)</td>
</tr>
<tr>
<td>Pm (elastic) (N)</td>
</tr>
<tr>
<td>Pm (Breakage) (N)</td>
</tr>
</tbody>
</table>

Fig. 4. Parameters for normal contact.

Fig. 5. Parameters for rotating and slipping contact.

Fig. 6. Impact force profiles measured at particle dropping test.

Fig. 7. Impact force profiles calculated with DEM method.
Impact forces measured and calculated are compared in Fig. 8. These data also show that calculations and experiments agree well. According to the model, breakage occurs only in the case of coke particle. The energy loss exists in the case of aluminum oxide ceramic sphere. This is not due to the breakage of particle but due to the yielding of the plate made of steel.

As a result of these analyses, it can be said that the breakage contact model is useful enough for the prediction of the mechanical phenomena at the collision of particle.

### 3.2. Fines Generation and Friction at Simple Shear Test

In order to confirm the authenticity of the model on the prediction of the dynamic behaviors of coke packed bed, a simple shear test was performed. The apparatus used is shown in Fig. 9. Cokes with the compressive strength of 50 MPa in Brinel hardness and the diameter of 30 mm was used.

As regards the fines generation, the size distributions of cokes after the tests were checked for all cases. The profile of the size distribution of cokes after simple shear test is shown in Fig. 10. All the size distribution was written in the same formula as follows:

\[ D(D_p) = \Phi(D_p/D_{p_{\text{max}}}) + (1 - \Phi)(D_p/D_{p_{\text{max}}})^\gamma D_p > D_{p_{\text{min}}} \]

\[ = \Phi(D_{p_{\text{min}}}/D_{p_{\text{max}}})^\gamma (D_p/D_{p_{\text{max}}})^\alpha D_p < D_{p_{\text{min}}} \ldots (38) \]

Here, \( D(D_p) \) is the cumulative undersize of \( D_p \) and \( \Phi \) is the fragments ratio. Powers \( \alpha, \beta \) and \( \gamma \) represent size distributions of fine fragments (fines), coarser fragments and parent cokes, respectively. \( D_{p_{\text{min}}} \) is the size of coke sample. \( D_{p_{\text{max}}} \) is the maximum size of fragments and is given beforehand as the half of the sample size because the maximum size of fragments does not exceed the half of sample size. \( D_{p_{\text{max}}} \) is the size to discriminate fines from coarser fragments. The size distribution pattern shows the coke sample after the breakage is separated into fragments with the size below \( D_{p_{\text{max}}} \) and parents with the size above the half of sample cokes. This results support the prediction that the dominant breakage mode is surface compressive breakage.

The dependence of these parameters on the mechanical load condition is summarized in Fig. 11. Most of the fragments were fines with the size of less than 200 \( \mu \)m. And the diameter discriminating fines from middle size fragments \( D_{p_{\text{min}}} \) and the power \( \alpha \) representing the size distribution of fines were kept constant. On the other hand, the value 200 \( \mu \)m is near the size of macro pore contained in the coke particle. These coincidences indicate that the fines in breakage fragments originate in the breakage of convexes because the convexes on coke surface are considered to be the edge of pore walls facing the surface. The only parameter to change with the mechanical load condition is the power \( \gamma \), which shows the weight of middle size fragments vary with the changes of mechanical load condition. According to the model, the mass of fragments originating in the breakage of particle itself increases with the increase of contact force. Therefore, the reason for the power \( \gamma \) to increase with the increase of compressive stress \( \sigma_a \) is considered to be due to the increase of the breakage of particle surface itself.

Three-dimensional DEM calculations were made for every experimental case with using Eqs. (16), (17), (36) and (37) as the expressions of normal contact force, rotating friction force and slipping friction force. Here, the shape of particles was assumed sphere. As for mechanical properties, actual value was used for the compressive strength and the Young’s modulus was set at 5 GPa.
time step was set at 2 μs. For the calculation of slipping friction coefficient, the height of broken convex \( d \) was set at 100 μm. This is because the main part of fragments have a size of less than 200 μm and this value matches with the size of coke pore. The compression strength of convex was set at 100 MPa, which is the double of the compressive strength of coke particle itself.

The friction force patterns measured and calculated are compared in Fig. 12. The calculation result agrees well with the experimental result. It must be additionally mentioned that such profile as shown in the figure was never obtained when Voigt Kelvin model was used for traction force.

Friction force \( \tau \), friction coefficient \( \mu \), fines generation ratio \( \Phi \) and fines generation energy \( (E_{f}/M) \) measured and calculated are compared in Fig. 13. As is clearly shown, calculations and experiments agree very well and especially, the friction coefficient was confirmed not constant but depend on normal stress in the formula as \( \sigma_{a}^{-1/3} \), as is predicted by the model.

These results confirm the usefulness of the model for the prediction of the dynamic behaviors of coke packed bed.

4. Conclusion

The mechanism of the breakage contact of coke particle was studied and a theoretical model to predict the breakage contact phenomena of coke particle has been developed.

The model could evaluate not only traction force at the contact of coke particles but also parameters to characterize contact breakage phenomena of coke particles.

Through the experiments, the authenticity of the model was well confirmed. The model would be useful for the clarification of the structure of coke packed bed and the evaluation of the fines generation in the blast furnace lower part.

**REFERENCE**