Numerical Study Using Discrete Element Method about Coke Particle Behavior in Cohesive Zone

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The simulation of cohesive zone in the blast furnaces is conducted using 2-dimensional discrete element method. The simulation is divided into two parts; (1) the group simulation of the flow of coke and ore particles in the cohesive zone when the reduced ore particles start to shrink and disappear with melting, and (2) the biaxial compression test simulations of breakable single coke particle with receiving x and y directional stresses which is evaluated from the group simulation. In addition, a gasification model is developed and combined with the coke model for the biaxial compression test simulation. The gasification process is simulated by removing element particles for a fixed amount.

In the group simulation, coke particles have been found to move actively not only the axial (horizontal) direction but also the radial (vertical) direction due to the elimination of ore particles in the melting zone. Due to these movements, the coke layers are severely distorted and the coke layer thickness is much decreased. The developed stresses on particles in the group simulation are recorded and this stress information is applied to a non-gasified and the gasified coke model to simulate the coke breakage behaviors. In the non-gasified case, both of the volume breakage and the surface abrasion are not observed. In the gasified case, the surface abrasion and fragmentation occur, but the volume breakage is not observed under the present simulation condition.

KEY WORDS: cohesive zone; discrete element method; DEM; biaxial compression test; group simulation; gasification model.

1. Introduction

The Blast Furnace (BF) is an efficient and useful operator reducing iron ores into hot metal, but once uneven gas flow occurs due to channeling, the BF can be damaged seriously. Thus, it is very important to grasp exactly what is going on inside the BF to secure the steady and safe BF operation. However, BF has tremendous size, and also it is not possible to interrupt the BF for interim examinations once it starts. Therefore, it is very difficult to investigate details of the phenomena occurred in the BF.

However, with ever more powerful computers and increasingly sophisticated software, the numerical simulation of BF behaviors becomes practical. As a complement of experimental studies, computational fluid dynamics (CFD) and discrete element method (DEM) can be helpful to determine the influence of each parameter, which is experimentally hard to obtain because dissociating one parameter from the others is almost impossible. Therefore, computational approaches using CFD and DEM have been widely used to investigate inside the BF and now become essential tools to study BF process.

Especially, DEM is a powerful method to simulate solid particles’ movement by calculating interaction forces between entities. Because DEM is an intuitive method, it is widely used in iron-making industries to simulate and examine the coke and iron ore particles’ movement in the BF. Through these studies, DEM has been confirmed to be a quite appropriate tool to analyze the solid particles behavior in the BF operation.

However, if it is supposed to develop a DEM model of an actual BF with the size of about 35 m height and 15 m radius and filling small DEM particles which have original coke and ore particle size of about 5 cm and 2.5 cm, respectively, then the DEM particles’ number exceeds the available calculation capacity for the simulation. To conquer this problem, Ueda et al. used a periodic partial BF model which had an 18° angled fan- shape cross-section and DEM particles with a 6 times bigger radius than the actual coke and ore particles to reduce the calculation burden for particle flow simulation inside a BF model. However, one of the important purposes of the present study is to investigate the coke breakage behaviors in the cohesive zone. Particles’ movement in the BF can be reasonably evaluated by the simulation with using the large particle sizes, but coke particle’s breakage behavior strongly depends on the size of coke. Thus, to obtain the reliable coke breakage results, the simulation with the actual size particles must be carried out.

One of the possible approaches to use actual size particle
simulation is narrowing the simulation domain down to a particular area to solve a concerning problem. For example, Mio et al.\(^3\) carried out DEM simulation by focusing on the coke and ore charging process from the bell to the top of the BF. Nogami et al.\(^1\) studied\(^4\) the effect of temperature and speed of gas on the formation of a raceway by using DEM simulation. In the present study, the coke breakage simulation has been carried out also by focusing on the small domain of the cohesive zone where an important particle flow change occurs by using the actual size particles.

In the real BF, when coke and iron ores which are charged layer by layer reach the cohesive zone, iron ores start to melt, and they are separated into liquid metal and slag, and these liquid phases flow downward through coke layers. At the same time, the reduction gases flow upward through coke layers. Therefore, coke layers act as passages of these countercurrent flows, and it is very important to maintain permeability to guarantee smooth flows. However, if the coke’s diameter decreases in the cohesive zone, it certainly deteriorates the gas permeability. For this reason, the movement and breakage of coke particles at the cohesive zone should be investigated more precisely for the stable BF operation. Especially, maintaining the gas permeability under the low coke ratio operation is critically important since the coke layer thickness becomes very thin. Thus, the information of coke behavior in the cohesive zone is essential for the low coke BF operation.

In addition, coke particles have been gasified during their descent by the solution loss reaction until they reach the cohesive zone. It was reported that a sudden decrease of coke diameter was observed at the cohesive zone’s temperature range (1 473 K–1 723 K), which was thought to be introduced the solution loss reaction as well as the same amount of volume breakage.\(^5\) One of the possible reasons of the volume breakage is that coke particles undergo sudden impacts by collapsing into the voids below the coke layer which is introduced when ore particles disappear by melting.

Since the complex reactions between gas, liquid and solid phases occur in the cohesive zone simultaneously, it is practically impossible to consider every reaction at the same time in a numerical simulation. For this reason, this study does not consider the gas flow and liquid drainage in the cohesive zone, but only consider the solid particles’ movement.

The present cohesive zone simulation using DEM consists of two parts. One is the group simulation which observes the movement of cookes and ore particles when ore particles enter the ore melting zone and start to melt. The other is the biaxial compression test simulation of a single coke particle about a specifically selected coke particle showing interesting movement during group simulation. The x- and y-directional stresses of the sample are continuously recorded during group simulation and this stress information is applied to a breakable single particle model to simulate coke breakage behaviors.

Unfortunately, the group simulation combined with a singular breakable coke particle cannot be carried out simultaneously, since not only the huge particle number increases calculation time, but it is also difficult to find proper material parameters and time step condition which satisfy both simulation models which have 100 times different scale order.

In addition, models in this study are initial stage at this moment, so this study’s main purpose is not achieving practical results but suggesting a new method to simulate particles’ behavior inside BF using practical particle size. For this reason, this study adopts very simplified BF situations arbitrary.

2. Numerical Model and Simulation Setup

2.1. Cohesive Zone Group Simulation

2.1.1. Numerical Model

The DEM simulation was carried out by using the commercial code PFC2D. This study adopts a 2-D model rather than a 3-D model because the group simulation requires long calculation time due to a large number of element particles. Also a 2-D model shows much clear cross-sectional vision, so it is much easier to observe particle flows inside the model. The basic element particle in a 2-D DEM is a disk-shape rigid body. This element particle is not breakable and not deformable, but it allows small overlap between particles to calculate interacting forces between contacting particles.

Figure 1 depicts mechanical entities to determine normal and shear forces between contacting particles. Among them, normal and shear stiffness (\(K^N\) and \(K^S\)) are calculated by Linear model\(^6\) as follows.

\[
K^N = \frac{K^A_n \cdot K^B_n}{K^A_n + K^B_n} \quad \text{......... (1)}
\]

\[
K^S = \frac{K^A_s \cdot K^B_s}{K^A_s + K^B_s} \quad \text{......... (2)}
\]

where \(K^A_n\), \(K^B_n\), \(K^A_s\) and \(K^B_s\) are normal and shear stiffness of particle A and B, respectively. Then normal and shear contact stiffness are related to the contact forces and relative displacements in the normal and shear directions as follows.

\[
F^N = K^N \cdot U^N \quad \text{......... (3)}
\]

\[
\Delta F^N = -K^N \cdot \Delta U^N \quad \text{......... (4)}
\]

where \(F^N\) is a normal directional contact force, \(U^N\) is a normal directional relative displacement, \(\Delta F^N\) is a shear contact force increment and \(\Delta U^N\) is a shear relative displacement change. The new shear contact force is found by summing the old shear force at the start of the time step with the shear force increment.

\[\frac{F^S}{K^S} \quad \text{damping} \quad \frac{F^S}{K^S} \quad \text{friction} \]

\[\text{Particle A} \quad \text{Particle B} \]

Fig. 1. Schematic view of the linear model between contact particles.
elastic force increment

\[ F' \leftarrow F' + \Delta F' \leq \mu |F'| \] ........................ (5)

where \( \mu \) is taken to be the minimum friction coefficient of the two contacting entities. If \( |F'| > \mu |F'| \), then slip is allowed to occur by setting the magnitude of \( F_s \) equal to \( \mu |F'| \). The details of the method are described in the PFC2D manual. 6)

2.1.2. Cohesive Zone Modeling Design

The present study focuses on the small area of the cohesive zone. Decreasing simulation domain has an advantage because not only it shows moving phenomena specifically but also it decreases the calculation time efficiently. Figure 2 shows the cohesive zone model used in this study. The model has about 2.8 m height and 2.0 m width, and left side represents the center side and right side is the shaft wall side. Coke particles and iron ore particles are piled up layer by layer at the 1:2 volume ratio following the suggestion of Geerdes et al. 7) Each coke layer or ore layer has same amount of coke or ore particles to maintain volume constant. Each coke layer has about 25 cm thickness, and it consists of 200 coke particles having 4.5–5.5 cm variation of the diameter. On the other hand, each ore layer has about 50 cm thickness, and it consists of 1 600 ore particles having 2.25–2.75 cm variation of the diameter. These sizes of cokes and ores are almost the same to the actual ones. Detailed coke and ore particles properties are listed in Table 1.

The model is surrounded by four walls. Usually, walls in a DEM simulation copy real frame of a container such as a BF, but this study had to use walls as imaginary boundaries which have different meanings for each case: The left wall means the center of the BF, so it is regarded as a symmetry line to have friction coefficient as zero. The right wall represents shaft wall side which becomes widen toward the bottom. The slope angle is determined following Yu et al.’s experimental device design to investigate the conditions during burden descent in the blast furnace. 8) The upper wall presses below particles at the fixed pressure 1 MPa. This value is determined by assuming that coke layers having 1 100 kg/m\(^3\) and ore layers having 4 400 kg/m\(^3\) are piled up at the ratio of 1:2 and 30 m height at the above. The top level particles are assumed to descent maintaining horizontal level. Finally, the bottom wall means the below particles, usually coke, supporting all above particles.

Conventional BF simulations fix observer’s view to boundary walls and move particles by charging particles to the top of simulation domain and by discharging them from the bottom. In this study, however, observer’s view moves along with the particles’ downward flow, so there is no addition of particles during simulation and the surrounding circumstances such as right wall and ore melting zone move upward. The left wall does not move because it is vertical and has friction coefficient zero.

Since the left side is the center side, the ore melting zone (OMZ) where ore particle’s size and properties are changed starts from the left bottom corner, and it is enlarged toward the right top corner. Figure 3 shows depiction of OMZ model and its calculation cycle mechanism. Actually, real cohesive zones have various size and shapes according to gas flow patterns. Thus, this study chooses an arbitrary slope angle, 63.4\(^\circ\) (tan\(^{-1}\) 2) as an example, and the OMZ rises up to 2.8 m maintaining a same increasing rate. The OMZ calculation cycle consists of following four steps and the cycle repeated 240 times. First, the right wall and the OMZ rise 0.0117 m (= 2.8 m / 240). Second, if some ore particle’s center enters into the OMZ, that ore particles are ‘melted’ by reducing the particle size and its stiffness value. The particle size is reduced 0.5% from the previous size, and the stiff-

| Table 1. Parameters of material and liner model for coke and ore particles in the group simulation. |
|-----------------|---|---|---|---|---|---|---|
|                | Coke | Ore |
| Diameter of particle (mm) | 45–55 | 22.5–27.5 |
| Density (kg/m\(^3\)) | 1 100 | 4 400 |
| Stiffness (MN/m) | 200 | 200 |
| Friction coefficient | 0.7 | 0.7 |
| Damping coefficient | 0.7 | 0.7 |
| Number of particles in a layer | 200 | 1 600 |
| Initial layer thickness (m) | 0.25 | 0.5 |

Fig. 2. Schematic diagram of the cohesive zone modeling for group simulation.

Fig. 3. Explanation of the ore melting zone calculation steps.
ness is reduced to the 25% of the original value. In other words, as an ore particle stays in the OMZ longer, the particle becomes smaller and smaller, but Young’s modulus does not change once it is reduced from 200 MN/m to 50 MN/m. Also, coke particle’s stiffness value is reduced in the same manner, but the size is not changed. The reduction of Young’s modulus is following the suggestion of Kurosawa et al.’s result. Third, if an ore particle’s radius becomes smaller than 9 mm, about 72% of the original size, the particle is eliminated to get a rapid result. Finally, 5,000 computation cycles with $1 \times 10^{-4}$ s calculation time step are executed to observe particle movement. The simulation steps are schematically shown in Fig. 3.

The total simulation time for one OMZ calculation cycle is 0.5 seconds. As a result, burden descends 2.8 m in 120 second, and descending velocity is about 23 mm/s. This value is a little bit higher than actual BF descending velocity, but it is quite acceptable to observe the effect of OMZ on the particles’ movement rapidly without any problem. Besides that, every parameter shown at above is determined in a stable range after carrying out several test simulations.

In the OMZ model, although small particles are eliminated while they still have not a little volume in ore melting zone, their effect is not so much outstanding because ore particles undergoing size reduction act as buffer between removed ore particles and coke particles.

### 2.2. Biaxial Compression Test for a Single Coke Particle

The group simulation introduced in the previous section uses non-breakable element particles, so it cannot carry out the particle’s breakage simulation directly, and an indirect method was applied. This study investigates the coke’s breakage behavior in the cohesive zone by applying stress information which is achieved from the group simulation to a breakable single coke model with considering the effect of gasification.

#### 2.2.1. Numerical Model

The element particle of DEM is non breakable, so a complex and breakable model requires assembling stage by gluing a large number of small element particles to the desired shape. Walls are used to form a mold to generate desired model shape by filling the inside of it with element particles. Walls are eliminated at the final model generating stage.

Element particles are connected at each contact site using a parallel-bond which is an imaginary elastic bridge to transmit both force and moment between element particles. The concept of parallel-bond is depicted at Fig. 4 where A and B are two contacting element particles, $R'$ is the parallel-bond radius, $t$ is a thickness and $F^N$, $F^\tau$ and $M^\tau$ are parallel-bond transferring normal force, shear force and moment, respectively. The parallel bond acts as a cementation-material between contacting two particles. It can be considered as a bunch of springs having constant normal and shear stiffness, uniformly distributed over a parallel-bond area. The parallel-bond is assumed to be broken (eliminated) when the normal or shear stress exceeds its corresponding strength. The parallel-bond radius ($R'$) is determined by the parallel-bond radius factor ($\alpha$) to be

$$R' = \alpha \times \min \left( R^A, R^B \right) \quad \text{(6)}$$

where $R^A$ and $R^B$ are the radius of two contacting particles. Parallel-bond stiffness ($k'$) is determined to give uniform stiffness with element particles by assuming to act in series at the parallel bond area. Therefore, parallel-bond stiffness is calculated by

$$k' = \left( \frac{k^A}{k^B} \right) \times \left( \text{Area of parallel bond} \right) \quad \text{(7)}$$

Theoretically, 2-D model does not have thickness, but PFC2D requires thickness value for calculation because it regards entities as disks having thickness. In this case, the area of parallel bond is $2R't$ where $R'$ is the parallel-bond radius and $t$ is the thickness. In addition, $k^A$ and $k^B$ have the same value, $k$. As a result, parallel-bond stiffness ($k'$) is determined to be

$$k' = \frac{0.5 \times k}{2R't} \quad \text{(8)}$$

#### 2.2.2. Biaxial Compression Test Design

**Figure 5** shows an example of the breakable single coke model. It has 5 cm diameter and consist of about 3,240 number of small element particles which have 0.5–1.0 mm diameter variation following the Gaussian distribution. The element particle’s properties are listed at Table 2. These parameters are decided to fit the apparent properties of coke particle in the group simulation. For example, the density of an element particle is determined to have an apparent density 1.5 MPa according to the suggestion of Sakai et al. As the coke model has diameter about 5 cm, this model locates between mili-structure and centi-structure, and it would have strength between 1–5 MPa. However, coke particles near the cohesive zone already have undergone certain amount of solution loss, so a little bit weak value is adopted. The porosity of the model is totally 25% which is the half value of usually know coke’s porosity 50% because 2D model cannot have that amount of high porosity. More details are well explained in the previous paper. To make
a highly porous and strongly bonded model at the same time, some special particles, so called ‘temporary pore-particles’, are inserted at the model assembling stage. Among 25% porosity, 15% are distributed naturally between closely packed particles, and the other 10% is taken by temporary pore-particles. The particles are spread randomly through the model and removed at the final stage leaving big pores among the coke model. These big pores act as important spots where stresses concentrate and cracks start. This study used three samples having 150, 175 and 200 temporary pore-particles named Pn 150, Pn 175 and Pn 200, respectively.

A coke model is surrounded by four walls, two vertical walls applying x-directional stress and two horizontal walls applying y-directional stress. The applied stress information is achieved by tracing a single element particle in the group simulation. After watching the recorded movie file of the group simulation, some actively moving coke particles were chosen at the middle part of the cohesive zone model to minimize the effect from boundary conditions. Actively moving particle means a particle shows various movements during simulation. After specified particles are selected, the same group simulation was carried out again recording x- and y-directional stress changes of those particular particles at the interval of 0.01 s. This recorded stress information is moved to the binary compressive test, and horizontal and vertical walls press or release the particle to apply the given stress at every 0.01 s. As the element particle dimension becomes small, the calculation time step is also decreased to 1×10−5 s, and total number of calculation cycle becomes 1.2 million cycles.

Following the suggestion of the International Society for Rock Mechanics,11) each directional stress of the specimen (σ) is calculated by the equation

$$\sigma = 0.636 \frac{P}{Dt}$$

where P is the normal force acting on the particle (N), D is the diameter and t is the thickness of the test specimen (mm).

### 2.2.3. Gasification Modeling

Besides the original coke model as shown in Fig. 5, gasified models are also investigated in the same way because coke particles are supposed to be drastically weakened after solution loss by reacting with gases at the cohesive zone. According to the result of Watakabe and Takeda’s experiment12) about coke gasification at 1473 K and 1773 K, reacting gases penetrate into a coke particle, and the amount of solution loss at each radius is linearly proportional to the gas penetration depth. In addition, the final penetration depth was affected by the reaction temperature. To be specific, when the reaction temperature is low, the gas easily penetrates into a coke particle, so the solution loss can occur at deep inside a coke particle. However, when the reaction temperature is high, most of reactions occur at the surface and the penetration depth decreases. It is because of the increased surface area due to the increased number of pores at the surface at the high reaction rate. The finding of the linear relation between the removed amount by the solution loss reaction and penetration depth was adapted to construct the gasification model in the present study. (See Fig. 6) The solution loss reaction was simulated by eliminating element particles from the original coke particle assembly. In the present study, the final total amount of removal coke particles was fixed to 10% of the total particles. As depicted in Fig. 6, the gasification process (coke particles removal) was conducted in five stages at every 20 seconds after first 20 seconds, and the compression tests were carried out for these coke assemblies.

During five gasification stages, the penetration depth \(d_p\) increases with maintaining the same length interval until it reaches to the target penetration depth \(d_{p,t}\). To get a linear solution loss graph according to the dimensionless penetration depth, the same amount of particles per unit area, \(\beta\), is eliminated for each gasification stage, where

\[
\beta = \frac{\text{total amount of removal particles}}{\frac{1}{5} \times (\text{area A}) + 4 \times (\text{area B}) + 3 \times (\text{area C}) + 2 \times (\text{area D}) + (\text{area E})}
\]

To be specific, during the first gasification stage \(g_1\), the first penetration depth becomes \(r_1\) and gasification stage occurs at the ‘A’ territory with the removal amount of \(\beta \times (\text{area A})\). In the same way, during the second gasification stage \(g_2\), the second penetration depth becomes \(r_2\) and gasification stage occurs at the ‘A’ + ‘B’ territory with the removal amount \(\beta \times (\text{area A} + \text{area B})\), … and during the final gasification stage \(g_5\), the final penetration depth becomes \(d_{p,5} = r_5\) and gasification stage occurs at the ‘A’ + ‘B’ + ‘C’ + ‘D’ + ‘E’ territory with the removal amount marked of \(\beta \times (\text{area A} + \text{area B} + \text{area C} + \text{area D} + \text{area E})\).
This study compares two samples having deep ($d_{p,t} = 0.5$) and shallow ($d_{p,t} = 0.3$) dimensionless target penetration depth. ($d_{p,t} = 0$ when gasification never occurs, and 1 when gasification occurs through whole sample). They are named as $d_{p,t} 0.5$ and $d_{p,t} 0.3$, respectively.

3. Simulation Results and Discussion

3.1. Particle Flows in the Cohesive Zone Group Simulation

Figure 7 shows typical particles’ flow during group simulation every 20 seconds. In the figure, three chosen single particles (A, B and C) are marked by closed circles to easily follow the particle’s movement. The group simulation analysis can be done by analyzing these particles’ flow (Fig. 7) and force distribution (Fig. 8), together.

At the beginning, shown in Fig. 7(a), the effect of OMZ is negligible yet. On the other hand the moving right wall is quite effective, so every coke and ore layers are expanded toward right side. However, As the OMZ becomes larger, the left part of the model flows downward rapidly. As a result, a diagonal slip plain is formed. An example of a slip plain is marked as a dash line in the Fig. 7(c). During Figs. 7(b)–7(d), the slip plane moves to the right side making fault planes on the coke and ore layers. As a result, coke layers become thin and stretch toward left bottom. During that, coke particles undergo severe friction between particles, and many voids are formed and disappeared. Unfortunately, the slip plane and particles’ movement are hard to visualize in shown figures, but are clearly confirmed by animations.

After ore particles in the OMZ shrink and finally disappear, coke particles reach the left wall, and layers meet each other (Fig. 7(e)). Because there is no way to remove coke particles in this model, coke particles are piled up like a dead man zone in the BF. Many voids are also formed and disappeared among the coke layers in the OMZ, especially near the dead man zone, because sudden movements occur when ore particles are removed. Finally, at Fig. 7(f), half of coke particles are gathered at the left side and the layer thickness becomes around half of the original thickness.

The right wall shifting is an important factor to determine coke layer shape as well as the OMZ. As shown in Fig. 7, the coke layer enters the OMZ after it already becomes thin and irregular shape. However, some part of coke layer especially the left part of top coke layer in Fig. 7(f) which is affected by only the OMZ keeps its original shape. Also, the right part of bottom coke layer which is affected by only the wall shifting keeps its original shape.

Figure 8 shows relative force distribution corresponding to Fig. 7. As a force line becomes thicker, more force is transferring between particles. The maximum force value is changed in the range of 60–120 KN, but usually stays in the range of 70–90 KN.
range of 80–95 KN. In Figs. 8(a)–8(d), strong forces are developed just below compressing upper wall, particularly, at the left side. Also strong vertical force lines are observed when particles are free from the effect of OMZ. At the beginning, strong forces are developed at the left side, but while the simulation goes on, they continuously move to the right side. As the OMZ becomes large, inclined force lines which are parallel to the OMZ boundary are observed near the OMZ boundary. Also strong horizontal forces are observed following coke layers in the OMZ. On the other hand, forces between ore particles in the OMZ are very weak because there are lots of empty spaces while ore particles shrink.

Overall, strong forces are appeared when the particles are not free to move even thought they are receiving force. Therefore strong forces tend to push the particles toward vertical direction to the force line where stresses are relatively small, and particles are free to move.

The observed coke particle movements were based on the 2-D simulation. The actual coke movements in 3-D might be different from those of 2-D since the produced vacant volume near the center due to the elimination of iron ore can be small compared with those near the wall in the 3-D case. This could make the radial (horizontal) directional coke movement slower and smaller than those in 2-D cases. However, the fundamental features of cokes behaviors in the cohesive zone such as the radial directional movement of coke particles, the thinning and severe distortion of coke layer would be the same to the 2-D simulation results, and only their degrees would be different.

3.2. X- and Y-directional Stresses on the Single Particle

Figures 9, 10 and 11 show x- and y-directional stresses applied on the A, B and C particles shown in Fig. 7(a), respectively. X- or y-directional stress is the sum of each directional normal stresses acting on the particle. The achieved stress data would be different according to the chosen particles, but these three samples’ stress data would be enough to explain coke particle’s behavior during the simulation by analyzing with Fig. 7. The notations g₁ to g₅ in the Fig. 10 represent the points where five gasification stages occur. It will be discussed at the next section. The common features of Figs. 9, 10 and 11 according to the circumstance changes are listed at the below.
First of all, relatively high y-directional stresses are observed at the beginning in most cases, and they are decreased rapidly and stay at low stress level at the early stage. (0.0–40 seconds range in Figs. 9 and 10, and 0.0–70 seconds range in Fig. 11). This is because particles are pushed by the y-directional stress to move rightward and settled at easy position as coke layers are expanded following right wall shifting. The stress disappears as the particle is settled down. Until this time, particles are not affected by the OMZ. This part can be interpreted as a coke layers above cohesive zone, which are descending maintaining their horizontal shape.

The effect of diagonal slip plane which is formed due to the right wall upward shifting and OMZ is appeared for 40–80 seconds range in Fig. 10 and 70–100 seconds range in Fig. 11. When these particles are located on the slip plane and swept downward, both x- and y-directional stresses soar rapidly and drop. Usually, rapid increments are observed when particles collide or rubbed with neighboring particles, and the following drops are observed when particles are swept with surrounding particles or fall into a void which is formed during active movement. The stress changes continue while coke layer deforms for 80–100 seconds range in Fig. 10 and 100–120 seconds range in Fig. 11. In the real BF situation, the slip plain may not be noticeable clearly because this simulation conditions are much simplified and much faster compared with BF conditions. Nevertheless, it shows well how coke particles move to radial direction and how coke layers become thin.

After the particle’s leftward movement is retarded after reaching to the dead man zone, x-directional stress increases sharply (90–100 seconds range in Fig. 9, 110–120 seconds range in Fig. 10), because they are pushed by particles coming after and there are no room to move. In the real dead man zone, not only high pressure from surrounding particles, but also melted iron affects coke particles. Therefore, it can be expected that coke particles in the dead man zone would be degraded easily to have a relatively small size.

In conclusion, the stress change reflects interaction between particles exactly. However, particularly high stress peaks are observed when particles undergo friction on the slip plane and compression at the dead man zone. On the other hand, when particles are swept with surrounding particles, the stress change stays in the moderate range even though it shows quite variable movement.

3.3. Abrasion of Gasified Coke Particle under the Biaxial Stress

The single coke particle model without a gasification treatment for the biaxial compression test is strong enough to stand group simulation’s stress, so any breakage is not observed during the test. However, once a coke sample starts to lose its element particles by the gasification treatment, the strength decreases drastically. Before applying the group simulation’s stress data to the gasified samples, constant biaxial pressures of 1 MPa and 0.5 MPa are applied to Pn 200- d90 0.5 and Pn 200- d90 0.3 samples, which have 25% porosity and 200 large pores, and the final result has
the penetration depth of 0.5 and 0.3, respectively, to verify the gasification model. **Figure 12** shows the sequential result of five gasification steps and 1 MPa biaxial compression to the Pn200-\(d_p,t\), 0.5 sample, and **Fig. 13** shows number of parted pieces per 20 seconds. In Fig. 13, the number of parted pieces increases quite linearly up to one hundred seconds with the constant stress of 1 MPa, but after then, sudden increase is observed for most cases. In the case of 0.5 MPa constant pressure, parted particles were not observed, but its number also suddenly increases after 100 seconds as like the case of 1 MPa. This sudden increase of the abrasion is also confirmed in the Fig. 12. As surface porosity increases drastically from 25% to 45.4%, some large pieces also start to be fragmented. (The \(d_{p,t}\) 0.5 samples undergo 4.08% particle lose of the gasified territory per each gasification while the \(d_{p,t}\) 0.3 samples undergo 6.24% particle lose.) If the particle assembly is ground with other assemblies, the outer surface of the assembly would be fragmented with the gasification, and a new surface will be appeared. This fragmentation can be accelerated and enhanced with increase of the porosity. Namely the size of the particle assembly is decrease not only by the gasification process (removal of the particles) but also by the enhanced fragmentation. Unfortunately, this gasification model do not consider newly generated surface, but this phenomena can be a reason of the observed sudden coke size drop at the cohesive zone range.5)

The group simulation’s stress data appeared in Fig. 10 is applied to the gasified samples, and the volume and number changes of parted pieces in every 20 seconds are shown in **Fig. 14**. The data shows large variation as a feature of the DEM simulation. This problem can be solved by increasing the sample number. Unfortunately, this study has few data because it takes several days to get a data, so only tendency is considered. The tendency is quite similar to that of Pn200-\(d_{p,t}\), 0.3 sample receiving 0.5 MPa constant pressure. At the beginning, any breakage is not observed because both stresses are low and decreasing even though first gasification was occurred. After 40 seconds, when the particle start to actively move, both volume and number of parted pieces are increased. At the early stage, the volume change is not so much outstanding compared with the number change. It means that the average size of parted pieces is small, and most of breakage form is an abrasion at contact sites. Usually, \(d_{p,t}\) 0.3 samples show much amount of abrasion compared with \(d_{p,t}\) 0.5 samples, especially at the early stage. However, after 100 seconds, when the coke particle approaches to the deadman zone, and its horizontal stress is increased, volume and number difference between two sample groups become ambiguous. Also, the volume fraction increase is much steeper than the number increase. It means that the average size of parted pieces becomes bigger. As surface porosities are increased up to 45.5% and 56.2% for \(d_{p,t}\) 0.5 and \(d_{p,t}\) 0.3, respectively, big size pieces which consist of more than 10 element particles are easily fallen out from the body. As a result, the size variation of parted pieces becomes large, and it is hard to find clear tendency for both cases.

The stress data in Fig. 10 is achieved under the condition of the constant diameter of the coke particles. As shown in Fig. 14, however, the coke particle diameter with the gasification treatment is not constant but decreases with time under the biaxial compression test. Then, the stresses under
the gasification treatment are expected to be different from those with the constant diameter. However, the change of the apparent coke particle diameter is relatively small, especially before 100 seconds, as shown in Fig. 14, and even at 120 seconds, the decrease of fragmented volume is only about 10%. Thus, it is possibly assumed that the developed stresses with gasification treatment during the group simulation may not be significantly different from those without the gasification treatment. Consequently, the stresses shown in Fig. 10 can be applicable for the stress test simulation with the gasification treatment as a first approximation.

4. Conclusion

The cohesive zone simulation is conducted using discrete element method. The simulation is divided into two parts; group simulation which observes the flow of coke and ore particles when ore particles enter the cohesive zone and start to shrink and disappear, and a biaxial compression test simulation of a breakable single coke particle model which is assuming 10% particle loss gasification through five stages. For the biaxial compression test, constant stress and specific coke sample’s x- and y-directional stresses which is extracted from the group simulation are applied. The results achieved in this study are summarized at below.

1) Coke layers in the group simulation are stretched and distorted due to the particle flows toward both sides which are caused by the ore melting zone and right wall shifting. Coke layers are deformed before the area enters into the ore melting zone. During the coke layer deformation, it undergoes continuously shifting slip plane. Also many voids are found to form and disappear in coke layers due to the active movement of coke particles.

2) A single coke particle can receive stresses up to 1 MPa, and the developed stress reflects the surrounding particle arrangement changes sensitively. When the particle slips on the slip plane and when the coke particle suddenly falls into a voids to fill it, both the x- and y-directional stresses change drastically. Also when the particles are pushed by approached coke particles after it reach to the deadman zone, the x-directional stress increased rapidly.

3) During the biaxial compression test on the breakable coke particle model, the amount of parted pieces are increased quite linearly at the early stage, but as the porosity exceeds certain level, relatively large fragmented pieces are parted without strong external force, and a new surface are appeared. This fragmentation can be accelerated and enhanced with increase of the porosity. This phenomenon may be a reason of sudden coke size drop at the cohesive zone range.

REFERENCES