Validation of Particle Size Segregation of Sintered Ore during Flowing through Laboratory-scale Chute by Discrete Element Method

Hiroshi MIO, Satoshi KOMATSUKI, Masatoshi AKASHI, Atsuko SHIMOSAKA, Yoshiiyuki SHIRAKAWA, Jusuke HIDAKA, Masatomo KADOWAKI, Shinroku MATSUZAKI and Kazuya KUNITOMO

1) Research Center for Advanced Science and Technology, Doshisha University, 1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321 Japan. 2) Kyoto Fine Particle Technology, Keihanna Interaction Plaza Inc., 1-7 Hikari-dai, Seika-cho, Soraku-gun, Kyoto 619-0237 Japan. 3) Department of Chemical Engineering and Materials Science, Doshisha University, 1-3 Tatara-miyakodani, Kyotanabe, Kyoto 610-0321 Japan. 4) Environmental and Process Technology Center, Nippon Steel Corporation, 20-1 Shintomi, Futtsu, Chiba 293-8511 Japan.

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In this paper, the particle size segregation of sintered ore during flowing through a laboratory-scale chute was investigated to validate the simulated results. The chute angle, installation of a damper at the outlet of the chute or the particle mixing condition were changed. The particles were segregated during flowing through the chute. The smaller particles were at the bottom wall of the chute, and the larger ones were on the smaller particles. The particle discharging velocity decreased with increasing the rolling friction in DEM, and the velocity also became uniformly. The particle discharging behavior under the large rolling friction was not spread, this phenomenon was not comparable with the experimental one. The distributed coefficient of rolling friction was determined by the distribution of rolled distance of sintered ore particle, and every particle in DEM had the different value according to the distribution of rolled distance. This method was effective for the sintered ores’ flow very much, and the simulated particle size segregation agreed with those of experimental very well, irrespective of chute angle, installation of a damper or particle conditions. Therefore, this simulation has been validated for the analysis of the granular flow in an ironmaking process.

KEY WORDS: chute flow; particle size segregation; Discrete Element Method; rolling friction; blast furnace; ironmaking process.

1. Introduction

Granular materials are very important materials in many fields, because they have special characteristics; such as large surface area, rich reactivity and flowability. When they are handled (e.g. conveying, charging, discharging or mixing) in the particulate processes, the particle segregation always takes place due to the differences of particle size, density or shape. Thus, the estimation of their phenomena and controlling their behavior are the most important factors for the efficient operation. Especially, the grasp of the particle segregation is the significant issue on the operation in an ironmaking process, which consists many conveyors and storages for carrying the granular materials to a blast furnace. The particle size segregation makes the inappropriate void fraction distribution in the burden during charging, and it leads to the fluctuation of gas flowability and the abnormal phenomena. Hence, many researches about the particle segregation at the charging process have been studied experimentally and mathematically. However, the experimental approach is laborious, because the scale of ironmaking process is huge and there are too many operational parameters and designs of system, which affect the particle segregation.

Discrete Element Method (DEM) is one of the most famous and reliable simulation methods for the numerical analysis of solid particle behavior. Although DEM gives useful information for the optimization of particulate processes and several researches on the ironmaking process had already studied, it still has two serious problems; the one is the calculation speed, the other is the particle shape. The speeding-up of DEM is possible to optimize the particle detection process and the program tuning, which were proposed by the authors. The multi-sphere or ellipsoidal particles are the commonest solutions for considering particle shape in DEM, and the usual commercial software packages have this kind of tool. However, it needs huge calculation time, therefore, the method for considering the effect of particle shape on flowing behavior with low calculation load is necessary for the large-scale calculation in the ironmaking process.

In this paper, the particle size segregation of sintered ore during flowing through the laboratory scale chute was investigated to validate the simulated results. The chute
angle, installation of a damper at the outlet of the chute or the particle mixing condition were changed. The distribution of coefficient of rolling friction was introduced to consider the effect of particle shape on the flowing behavior in DEM based on the spherical particle. The effect of rolling friction on the flowing behavior and the particle size segregation were discussed.

2. Experimental

A laboratory scale chute was used in the experimental work for the analysis of the particle size segregation during flowing through the chute, whose size was about one-third of actual one in a blast furnace. The horseshoe-shaped chute, having 1780 mm in length, didn’t have a rotating system and a damper (length: 200 mm) could be installed at the outlet of the chute, as shown in Fig. 1. 150 kg of the sintered ore particles, which were sieved in the range from 2 to 3 mm, 5 to 10 mm or 15 to 20 mm, were charged in the hopper. They were stacked in the layer, and the smaller particles were located at the bottom. The chute angle, $\theta_c$, was changed as 40° or 51°, and the condition for the installation of the damper was $\theta_d$=45° without it. Two particle-mixing conditions, which are shown in Table 1, were examined. The particle discharging flow was recorded by using the high speed video camera (TroubleShooter, FASTEC IMAGING CORPORATION) under 250 fps, and the discharging velocity of the particles were measured from the particle trajectories of each image. The velocities were measured from all visible individual particles in the image, regardless of the particle size. The discharged particles from the chute was collected by 30 sampling boxes, as shown in Fig. 1. The collected particles in every box were sieved and their masses were measured.

The sintered ore particles were also dropped on an oblique plate with 30° against horizontal to investigate the effect of particle shape on the rolled distance (see Fig. 2). The sintered ore particles from 5 to 15 mm in diameter were examined, and the distribution of the rolled distance was obtained.

3. Simulation

3.1. Discrete Element Method

Discrete Element Method (DEM) is one of the most popular and reliable simulation methods for the numerical analysis of solid particle behavior. This simulation method consists of the idea of determining the kinematic force to each finite-sized particle. The main calculation of DEM consists three steps; i.e., 1) particle detection, 2) calculation of forces, 3) update of trajectories, and these processes are looped until $t=t_{\text{max}}$. The contact between two particles is given by Voigt model, which consists of a spring-dashpot and a slider for the friction in the tangential component. The contact forces, $F_n$ and $F_t$, are calculated by following equations.

$$ F_{n,ij} = \left( K \Delta u_{ij} + \eta \frac{\Delta u_{ij}}{\Delta t} \right) n_{ij} \quad \text{(1)} $$

$$ F_{t,ij} = \min \left\{ \mu |F_{n,ij}| t_{ij}, K_{ij} \left( \Delta u_{ij} + \Delta \phi_{ij} \right) \right\} t_{ij} \quad \text{(2)} $$

Where, $K$ and $\eta$ mean the spring and the damping coefficients. $\Delta u$ and $\Delta \phi$ are a relative translational displacement of gravitational center between two particles and a relative displacement at the contact point caused by the particle rotation. $\mu$ is the frictional coefficient. $n_{ij}$ and $t_{ij}$ denote the unit vector from the $i$-th particle to the $j$-th one in the normal and the tangential components. The subscript $n$ and $t$ also denote the normal and the tangential components. The translational and rotational motions of each particle are updated by following equations.

$$ \mathbf{v} = \frac{\sum F}{m} + \mathbf{g} \quad \text{(3)} $$

<Table 1. Particle mixing condition in the experimental work.>

| Condition | 2-3 mm [kg] | 5-10 mm [kg] | 15-20 mm [kg] |
|-----------|-------------|-------------|-------------|
| Condition 1 | 0 | 75 | 75 |
| Condition 2 | 22.5 | 60 | 67.5 |

<Fig. 1. Schematic diagram of laboratory scale chute.>

<Fig. 2. Schematic diagram of particle rolling test.>
Where, \( v \) is the vector of a particle velocity, \( F \) is the contact force acting on a particle, \( m \) and \( g \) mean the mass of a particle and the gravitational acceleration, \( \omega \) is the vector of angular velocity, \( M \) and \( I \) denote the moment caused by the tangential force and the moment of inertia.

### 3.2. Rolling Friction

The shape of particle in DEM is usually assumed to be spherical due to the ease of contact detection or calculation of contact force, although that of sintered ore particle is completely irregular. The best solution for considering the particle shape in DEM is to model the exact particle shape. However, it is very difficult to do them, and the calculation load becomes extremely large, hence it is not suitable for the simulation in the ironmaking process, because there are billions and billions of particles. The particle shape affects mainly the flowing behavior and the particle packing fraction. The new method for considering particle shape on the packed bed having low calculation load was proposed, and the former one is more important in the case of chute flow. Thus, its effect on the particle motion was considered by setting the proper rolling friction for the sintered ore particle, and it is given by Eq. (5).

\[
\dot{\omega} = \sum_{i} \frac{M}{I} 
\]

Where,\( M_{ij} \) is the moment caused by the rolling friction, \( b \) is a radius of contact area, and \( \sigma_i \) denotes the coefficient of rolling friction. \( \sigma_i \) for the spherical particle is 1.7–2.0; usually 1.9 in this cord. However, \( \sigma_i \) for the sintered ore particles, which are simulated in this work, should be used individual values because the shape of each particle is totally different.

### 3.3. Simulation Condition

The particle flows in the hopper and the chute were simulated by using DEM, and the particle size segregation in the simulation work was compared with the experimental results to validate the properties in this simulation. The geometry of the chute was completely same as that of experimental, and the size of sintered ore particle was determined to be the median diameter of sieved particles; i.e. 2.5, 7.5 or 17.5 mm. Young’s modulus, Poisson’s ratio or density of particle were 35 GPa, 0.25 or 3 300 kg/m³, respectively. The total mass of particles was 150 kg, and the particle mixture conditions were same as those in Table 1, and the number of particles in the simulation is tabulated in Table 2.

### 4. Results and Discussions

Figure 3 shows the picture of particle discharging behavior from the chute under the condition of \( \theta = 51^\circ \) in the experimental work. Figure 4 shows the mass of collected sintered ore particles in each sampling box. The sampling box is numbered from the upper one; the highest one is No. 1, and the lowest one is No. 30. It is found from this figure that the larger particles are collected by the upper boxes, while the smaller ones are in the lower boxes. Because the particles are segregated during flowing through the chute; i.e. the smaller particles are at the bottom wall of the chute, and the larger ones are on the smaller particles. This phenomenon was observed by the high-speed video recording, which is shown in Fig. 5. The larger particles were colored white at this recording work. It is seen that the smaller par-
particles are discharging from the bottom of chute. The velocity of discharging particle was also measured from the images, and Fig. 6 shows its distribution. The particles were discharged from the chute with 3.0 to 4.5 m/s in velocity, and the mean velocity was about 3.7 m/s. The tendency of particle size segregation is similar when the chute angle was changed to 40°, which is shown in Fig. 7. The distributions of collected particles become narrow because the gravitational force is more dominant during flowing through the chute. The particle discharging flow was not so dispersed, and then the particles were charged to the boxes straightly. When a damper was installed at the outlet of the chute with 45° (Fig. 8), the particle size segregation collected in the sampling boxes became less than those in the conditions without it (Fig. 4 or 7), because the particles are mixed at colliding the damper. There is a small peak at upper sampling boxes; this is caused by the particles that didn’t hit on the damper.

Figure 9 shows the snapshots of particle flowing behavior in the chute under the different coefficient of rolling friction, \( \alpha_i \), in the simulation work. All particles have same \( \alpha_i \) in each condition, and the colors of these figures designate the particle velocity. It is found that the particle velocity decreases with increasing the rolling friction, and the velocity also becomes uniformly. The particle has large resistance for moving when \( \alpha_i \) is too large, hence the particle doesn’t have freedom to move individually. This tendency is seen in the snapshots of side-view of discharging behavior from the chute, as shown in Fig. 10 (black: 7.5 mm, gray: 17.5 mm). The particles under large \( \alpha_i \) are not spread comparing with the discharging behavior in the experimental work (Fig. 3). Thus, too large rolling friction is not suitable for the case of sintered ore’s flow. Figure 11 shows the snapshots of discharging behavior from the hopper under \( \alpha_i = 5.0 \). The mass flow was observed not only in the simulation work also in the experimental work. Figure 12 shows the relation between the discharging time from the hopper and the coefficient of rolling friction. The discharging time.
increases with increasing the rolling friction because the particles have the difficulty for moving under the large rolling friction. The mean discharging time in the experimental work was obtained to be 3.5 s, then around \( \alpha = 20 \) corresponds to the experimental result. However, as discussed above, the large rolling friction is not suitable for the sintered ore, when all particles have same \( \alpha_i \). Precisely, the shape of sintered ore particle is completely irregular, and there is no same shape, therefore each particle should have different rolling resistance.

Figure 13 shows the distribution of rolled distance of sintered ore particles with a parameter of particle size, when the particles were dropped on the oblique plate with 30° against horizontal. They give the skew distribution, and it is found that the particles could hardly roll on the plate due to their complicated shape. The particle size affect on the rolled distance very little in these cases, because the effect of particle shape is more dominative. The rolling frictions of particles in the simulation should be related to this result. Figure 14 shows the distribution of rolled distance...
of all particles, and the median of this distribution is about 57 mm. Consequently, $a_i = 20.0$ is determined to be the median value of the distribution of rolling friction, because the discharging time under $a_i = 20.0$ correlated with the experimental result. It was given that the particle discharging velocity from the chute under $a_i = 32.5$ is about 3.0 m/s or more. The minimum discharging velocity in the experimental is around 3.0 m/s (see Fig. 6), thus, this value is determined to be the largest $a_i$ of the distribution of rolling friction. Therefore, the distribution of $a_i$ is given as Fig. 15. Every particle in the simulation has the different value of $a_i$ according to this distribution, irrespective of the particle size, by generating the random number at the beginning of the calculation.

Figure 16 shows the snapshot of particle discharging behavior from the chute under the condition of $\theta_c = 51^\circ$, when the particles have the distributed coefficient of rolling friction. The particle discharging behavior seems to be similar to that of experimental (Fig. 3). Figure 17 shows the snapshots of particle flow in the chute for the last several particles. It is seen from these figures that the particles slide on the chute with grouping each other, and the some particles are stopped by the strong rolling friction and then they start to move again by being pressed from the following particles. This phenomenon was usually observed in the experimental work, however, it was not given under the condition of uniformed rolling friction in the simulation. Therefore, the distributed rolling friction is worthy for the simulation of the sintered ore’s flow. Figure 18 shows the distributions

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**Fig. 13.** Distribution of rolled distance of sintered ore particles with a parameter of particle size.

**Fig. 14.** Distribution of rolled distance of sintered ore particles.

**Fig. 15.** Distribution of coefficient of rolling friction.

**Fig. 16.** Snapshot of particle discharging behavior under 51°.

**Fig. 17.** Snapshots of particle behavior in the chute for last several particles.

**Fig. 18.**
of collected particles in all sampling boxes, under $\theta_c=40^\circ$ or $51^\circ$. It is found that the larger particle are collected at upper boxes, on the other hand, smaller ones are lower boxes. These tendencies are quite similar to the experimental results (Fig. 4 or 7). The width of the distribution in the simulated result seems to be narrower than that of experimental, because the shape of actual particle is completely irregular, then some particles have the difficulty to come in the boxes. Figure 19 shows the snapshot of particle behavior when the damper was installed at the outlet of the chute ($\theta_c=45^\circ$, $\theta_s=51^\circ$). The particles are mixed at the time of impact on the damper, and the mixture of particles is falling into the sampling boxes. This tendency is also given in Fig. 20, and the particle size segregation becomes less than that of without the damper, irrespective of chute angle. The distributions agree with the experimental results very well comparing with Fig. 8. Figure 21 shows the distribution of collected particles in the sampling boxes (Fig. 21(a): experimental, Fig. 21(b): simulated), when the segregation of three kinds of particles was examined under $\theta_c=51^\circ$. The relative positions of each distribution in these figures are comparable, and the simulated particle size segregation by using DEM agrees with the experimental results very well. Off course, although there are little errors between them, these results are correlated in spite of using the spherical particles. Therefore, it can be concluded that the distributed rolling friction work for the simulation of sintered ore's flow, and this simulation has been validated for the analysis of the granular flow in an ironmaking process.

5. Conclusions

In this paper, the granular flow in the laboratory scale chute was analyzed to validate the simulated behavior of
sintered ore particles. The rolling friction of the particle and the particle size segregation during flowing through the chute were discussed. The followings are summaries of this work.

1. The particles are segregated during flowing through the chute. The smaller particles are at the bottom wall of the chute, and the larger ones are on the smaller particles. When a damper was installed at the outlet of the chute with 45°, the particle size segregation collected in the sampling boxes became less than those in the conditions without it, because the particles are mixed at colliding with the damper.

2. The particle discharging velocity decreases with increasing the rolling friction, and the velocity also becomes uniformly. The particle discharging behavior under large rolling friction is not spread. Thus, the unformed rolling friction is not suitable for the simulation of sintered ore’s flow.

3. The distributed coefficient of rolling friction was determined by the distribution of rolled distance of sintered ore particle, and every particle in DEM had the different value according the distribution of rolled distance. This method is effective for the sintered ores’ flow very much.

4. The simulated distributions of collected particle agree with those of experimental very well. Therefore, this simulation has been validated for the analysis of the granular flow in an ironmaking process.

REFERENCES

1) Y. Okuno, S. Matsuzaki, K. Kunitomo, M. Isoyama and Y. Kusano: Tetsu-to-Hagané, 73 (1987), 91.
2) T. Sawada, T. Uetani, S. Taniyoshi, M. Miyagawa and M. Yamazaki: Tetsu-to-Hagané, 78 (1992), 1337.
3) M. Hattori, B. Ino, A. Shimomura, H. Tsukiji and T. Ariyama: Tetsu-to-Hagané, 78 (1992), 1345.
4) P. A. Cundall and O. D. L. Strack: Geotechnique, 29 (1979), 47.
5) T. Nouchi, T. Sato, M. Sato, K. Takeda and T. Ariyama: ISIJ Int., 45 (2005), 1426.
6) Z. Zhou, H. Zhu, A. Yu, B. Wright, D. Pinson and P. Zulli: ISIJ Int., 45 (2005), 1828.
7) H. Mio, K. Yamamoto, A. Shimosaka, Y. Shirakawa and J. Hidaka: ISIJ Int., 47 (2007), 1745.
8) D. Pinson and B. Wright: Proc. Discrete Element Methods 07, Min-

erals Engineering International (MEI), Falmouth (UK), (2007), CDROM.
9) H. Mio, A. Shimosaka, Y. Shirakawa and J. Hidaka: J. Chem. Eng. Jpn., 38 (2005), 969.
10) H. Mio, A. Shimosaka, Y. Shirakawa and J. Hidaka: J. Chem. Eng. Jpn., 39 (2006), 409.
11) H. Mio, A. Shimosaka, Y. Shirakawa and J. Hidaka: Adv. Powder Technol., 18 (2007), 441.
12) H. Mio, A. Shimosaka, Y. Shirakawa and J. Hidaka: J. Soc. Powder Technol., Jpn., 44 (2007), 206.
13) L. Vu-Quoc, X. Zhang and O. R. Walton: Comp. Meth. Appl. Mech. Eng., 187 (2000), 483.
14) M. Klemmer and J. F. Favier: Int. J. Num. Meth. Eng., 51 (2001), 1423.
15) G. G. W. Mustoe and M. Miyata: J. Eng. Mech., 127 (2001), 1017.
16) Y. Song, R. Turton and F. Kayihan: Powder Technol., 161 (2006), 32.
17) W. Wu and D. Morrison: Proc. Discrete Element Methods 07, Min-

erals Engineering International (MEI), Falmouth (UK), (2007), CDROM.
18) P. W. Cleary: Powder Technol., 179 (2008), 144.
19) M. Akashi, H. Mio, A. Shimosaka, Y. Shirakawa, J. Hidaka and S. Nomura: ISIJ Int., 48 (2008), 1500.