Hindawi
Shock and Vibration
Volume 2023, Article ID 2838179, 14 pages
https://doi.org/10.1155/2023/2838179

Research Article

Numerical Simulation of the Collision Breakage Process between the Agglomerate and Hammer in a Hammer Crusher Using DEM

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Received 6 April 2023; Revised 4 July 2023; Accepted 5 July 2023; Published 25 July 2023

Academic Editor: Manoj Khandelwal

This paper focuses on simulating the collision breakage process between the agglomerate and hammer in a hammer crusher by the discrete element method (DEM) as the interaction between particles. This enables us to consider the energy change in the collision breakage process of the hammer. The agglomerate model is built by using the EDEM 2.7 software according to the principle of closest packing in crystallography, while the hammer model is modeled into an assembly of different sizes of spherical particles to make the collision breakage process between the agglomerate and hammer as the one of interrelation of particles. With these models, we mainly investigated collision force, collision impulse, energy breaking agglomerate, and the relationship between the specific breakage energy and agglomerate damage ratio. The collision force is represented as Gaussian function, the collision impulse is represented by the function of the mass ratio of agglomerate to hammer and the product of agglomerate mass and collision velocity, and the relationship between the specific breakage energy and agglomerate damage ratio is represented by exponential function. Finally, it can be seen from this study that, when crushing the agglomerate by hammer impact, it is necessary to increase the specific breakage energy by 1.75 times in order to increase the agglomerate damage ratio from 85% to 90% but 2.13 times in order to increase 95%. The proposed method can be used for the further development and design of the various types of crusher.

1. Introduction

It can be said that many production means and consumer goods used today are actually associated with comminution. For example, a machine tool is made of steel, the production of which is started from mining and comminution of iron ore. Also, the production of cement used for construction of houses and buildings where we live and work begins with crushing of limestone, resulting in grinding of a cement clinker. Coal comminution is still included in the production of electricity indispensable for modern production and life. Thus, it can be said that comminution is an essential part in many fields of economy, consuming a greater amount of energy. Therefore, it is very important to reduce energy consumption of a comminution machine by studying its working process on scientific basis.

Breaking in a hammer crusher, a kind of machine for comminution, occurs fundamentally due to collision between the hammer and agglomerate. So it is of great importance to study the collision breakage process between the hammer and agglomerate. In particular, the accurate calculation of the energy loss quantity of a hammer in the collision breakage process is one of the key issues in determining the breakage power of a hammer crusher.

In the past, several studies have been conducted to calculate the productivity and demand output of hammer mills. Endou et al. [1] studied the relation between the increasing rate of holdup and the material-feeding rate in a hammer mill through the experimental stage to define the maximum crushing capacity as the maximum feed rate at which holdup does not change but is maintained constantly according to time. Endou [2] studied to link the

maximum holdup and mean residence time in the hammer mill to characteristics of raw materials to obtain the empirical formula for estimating the maximum crushing capacity of the hammer mill. Also, Endou [3] linked electric energy expenditure per dry weight of broken feed material to the mean residence time in the hammer mill to obtain the empirical formula for estimating momentary electric power needed in breakage by using the hammer mill. Dey et al. [4] carried out a systematic study on the comminution of soft (coal) and hard (iron ore) materials to investigate the bulk comminution features of the hammer mill. The studies were on the reduction ratio, energy consumption, fine generation, effect of feed rate given to breakage capacity, and rotator speed on the viewpoint of median size. Moreover, the investigation was the Rosin–Rammler type of size dimension distribution on the product in the hammer mill. The reduction ratio and the specific energy expenditure are linearly related, the slope of which is inversely related to the Bond Index of the material. The quantity of fines generated in the crusher can reflect the degree of attrition in the mill, which is an indirect measure of the mill wear. Shi et al. [5] studied the energy model of a hammer mill obtaining a crushing model with dynamic internal recirculation by combining breakage classification function, screen classification function, and breakage distribution function. Austin [6] studied the relation between the power consumption and the product size distribution in consideration of the repeated strike of the hammer on the solid material that is not crushed at one strike. Hong and Kim [7] presented a method evaluating the numerical value of the magnitude of a vibration component contained in the rotor angular velocity of a hammer crusher and a new structure to remove them.

After Cundall and Strack [8] used DEM for studying the behavior of granular assemblies, great successes were made by widely applying this method to bulk solid study, and an agglomerate modeling method by DEM was created to activate the study on the breakage process. Studying on the breakage process by DEM in comminution devices consists of two steps: one is to make an agglomerate model to be broken and the other is to consider its breakage process by breaking this agglomerate model into a comminution device model.

First, previous works have presented several studies to make an agglomerate model by DEM. Jiménez-Herrera et al. [9] described three methods for making an agglomerate model by DEM. These are the methods of making BPM (bonded-particle model), FBM (fast-breakage model), and PRM (particle replacement model). They said that FBM is a model of instantaneous breakage that uses the Laguerre–Voronoi tessellation to segment the particle into 2D polygons or 3D polyhedral, and the first time the total energy of the collision is higher than the energy required for fracture. Contacts between individual particles are described by using the linear hysteresis contact model. PRM, which Cleary [10] put forth and Cleary and Sinnott [11] supplemented, has been successfully used to describe breakage of particles. This model, when reaching a satisfactory breakage condition, is replaced by progeny fragments, which could be either shaped as individual spheres or clumped spheres. The size distribution of progeny particles can be determined from breakage test data. BPM formulated by Potyondy and Cundall [12] is a foundational one for modeling agglomerate. They explained that BPM simulates the mechanical behavior of a collection of nonuniform-sized circular or spherical rigid particles that may be bonded together at their contact points. Also, they supposed that BPM mimics the mechanical behavior of a collection of grains joined by cement and the cement-based portion of the force-displacement behavior at each cemented contact was described as the following five parameters that define a parallel bond: normal and shear stiffness per unit area, $\overline{k}^n$ and $\overline{k}^s$; tensile and shear strengths, $\overline{\sigma}_c$ and $\overline{\tau}_c$; and bond-radius multiplier, $\overline{\lambda}$. In addition, these were called the microproperties of BPM. To implement the BPM model, in several previous works, they randomly generated spherical agglomerates according to a certain size distribution, made spherical an agglomerate model by massing them into the center under the centripetal force, and studied the impact breakage process with this model. Thornton et al. [13] have considered rebound, fracture, or shattering by impacting orthogonally against target wall agglomerates whose average diameter is 1.113 mm, packing efficiency is 0.653, and average coordination number is 4.879. Mishra and Thornton [14] made 4 agglomerates (average radius 0.22 mm) where solid fractions are 0.602, 0.583, 0.571, and 0.537, respectively, and corresponding contact numbers are 12 400, 8 329, 7 653, and 6 251, respectively, with 5 000 particles 16~24㎛ in size and impacted orthogonally against a target wall to study the effects of impact velocity, solid fraction, contact density, and the local arrangement of particles near the impact zone. Moreno et al. [15] proved that the damage ratio only depends on the normal component of the impact velocity and the tangential component has little effect by analyzing the breakage feature of oblique impact and the effect of bond strength between agglomerates with agglomerates made of 3 000 particles whose radius is 0.907 mm, packing efficiency is 0.546, and coordination number is 5.617. Yang et al. [16] proposed a number of empirical equations relating to packing density, coordination number, and bonding force to particle size based on analyzing the effect that the number of particles and centripetal force influence packing efficiency when agglomerate is formed. Tong et al. [17] statistically investigated the effects of the impact angle and velocity on the agglomerate breakage in terms of the structural evolution and final breakage pattern of agglomerates by impacting agglomerates whose packing efficiency is 0.552 and diameter is about 100 μm, 200 times in different velocities and angles on a target wall. Spettl et al. [18] suggested the combined stochastic microstructure modeling method and studied the breakage behavior of spherical agglomerates under uniaxial compression depending on their microstructure studied statistically. They developed a flexible stochastic model to generate agglomerates with various types of microstructures and investigated the effect

of the primary particle size distribution on agglomerate strength and breakage behavior. In particular, the size distribution of primary particles was specified by a mixing of two fixed particle sizes. The model construction ensured that the size and mass of the agglomerate as well as primary particles and binder content could remain constant in all experiments. Quist and Evertsson [19] implemented the modeling of ore agglomerates by BPM. They showed mono distribution, Gaussian, and bimodal ones for the packing structure of particles as shown in Figure 1. The large part of the bimodal distribution was set to a mean sphere diameter size of 18 mm and a standard deviation of 1.8 mm. The smaller part of the bimodal distribution was set to a mean size of 4.8 mm and standard deviation of 1.2 mm. The packing density of the fraction particle bed was calculated to be 0.76. Jiménez-Herrera et al. [9] packed the closest particles arranged on one layer the same as in the mono distribution of Quist and Evertsson [19] to compare BPM, FBM, and PRM with each other by making an agglomerate in a method of laying such a layer several times as shown in Figure 2.

Next, some studies have been conducted to consider the crushing processes in comminution devices by DEM. Djordjevic et al. [20] simulated the particle movement and calculated the velocity and energy distribution of collision in two types of impact crusher by applying the DEM technique: the vertical shaft crusher and the horizontal shaft mill. The study on the hammer crusher based on the DEM technique was conducted by Sinnott and Cleary [21]. They simulated the flow of materials and the breakage by using the DEM replacement breakage model, which is proposed by Cleary [10] and described by Cleary and Sinnott [11], thus resulting in the detailed results such as energy prediction, the product size, throughput, and wear. Quist and Evertsson [19] made a model of rock agglomerate by BPM and calibrated it by conducting an experiment of breaking a single particle in a laboratory to obtain the size distribution of products, the pressure subjected to mantle, and power consumption by conducting a breakage simulation with a Svedala H6000 cone crusher model. Refahi et al. [22] and Metzger and Glasser [23] investigated the breakage behavior and breakage energy using DEM in the jaw crusher and ball mill, respectively.

The above studies on collision crushing in the hammer crusher by DEM considered the collision process between hammer modeling in wall and agglomerate. However, the wall in the DEM model has no mass, so its energy cannot be considered. Thus, the aforementioned simulation methods cannot calculate the energy change of the hammer in the collision process.

The aim of studying the collision crushing between the hammer and agglomerate in the hammer crusher is to estimate the breakage degree of agglomerate due to collision and is to predict the energy consumption in hammer crusher by obtaining the energy loss of hammer in the collision process. Therefore, it is of theoretical and practical significance to calculate the lost energy of the hammer in the collision process between the hammer and agglomerate.

2. Simulation of the Collision Breakage Process between the Hammer and Agglomerate

In this paper, EDEM 2.7 was used to simulate the collision breakage process between the hammer and the agglomerate; it is simulation software of particle mechanics based on discrete technologies. The contact model used in the simulation was Hertz–Mindlin with bonding embedded in EDEM. Figure 3 shows a model of collision between the hammer and agglomerate. As shown in Figure 3, this model consists of a hammer of mass m_1, an agglomerate of mass m_2, and a rotor. The hammer is hung on the rotor by the pivot O_1, and the rotor rotates around the fixed axis O with constant angular velocity ω. $R = 150$ mm is the distance from the pivot of the rotator O to that of the hammer O_1, and $L = 125$ mm is the distance from the pivot of the hammer O_1 to the collision point between the hammer and agglomerate A. Just before collision, the hammer pulls out into the radius-direction of the rotor due to centrifugal force and has the same angular velocity as the rotors. At this time, the velocity of the agglomerate is zero.

2.1. Hammer Model. What is important in this collision model is to model the hammer as not wall, but particle. The simulation bodies in DEM contain the particle and wall. Here, the particle has mass and energy, but the wall does not have mass, so energy cannot be discussed. Djordjevic et al. [20] and Sinnott and Cleary [21] modeled the hammer of the crusher as the wall, so they could not consider the energy change of the hammer. Therefore, if the hammer is made into a particle model with an assembly of spherical particles of different sizes to simulate the collision breakage process between the agglomerate and hammer, we can study the energy change of the hammer in the collision breakage process, because the collision becomes the breakage process between particles corresponding to DEM theory. The hammer was made with assembling various sizes of spherical particles (radius: 5 mm, 7.5 mm, and 10 mm) according to types and sizes of hammer, as shown in Figure 4. The material of spherical particles is steel with a density of 7,800 kg/m^3, Poisson's ratio of 0.28, and a shear modulus of 8.2×10^4 MPa.

The model for the hammer crusher is created by inserting a cylindrical body of 20 mm in diameter into the hole of the hammer and rotating it around the pivot O of the rotator.

2.2. Agglomerate Model. The principle of crystallography is used to make an agglomerate model by imitating the internal crystal structure of mineral materials. In [24], the principle of closest packing is that atoms in a crystal structure attempt to arrange themselves in a manner, which fills space in the most efficient way. It describes that minerals have the crystal structure, so the internal structure of minerals composed of

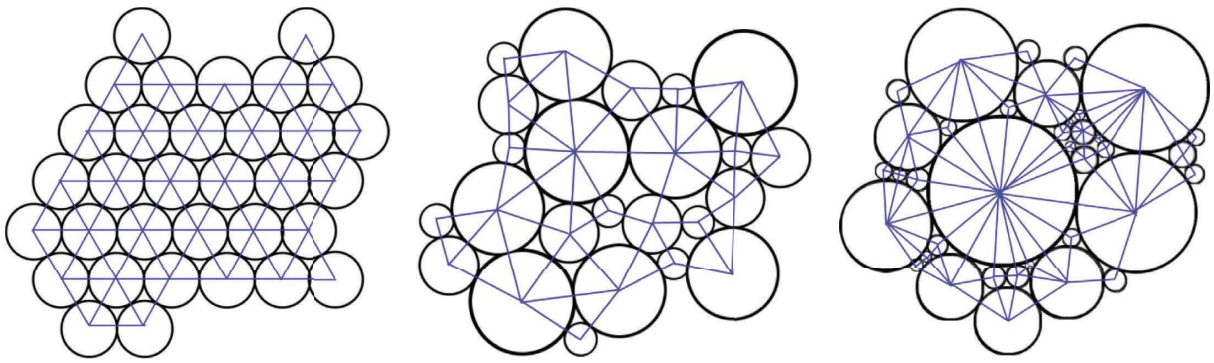

Figure 1: Schematic illustration of three types of packing structures: (a) mono distribution, (b) Gaussian distribution, and (c) bimodal distribution.

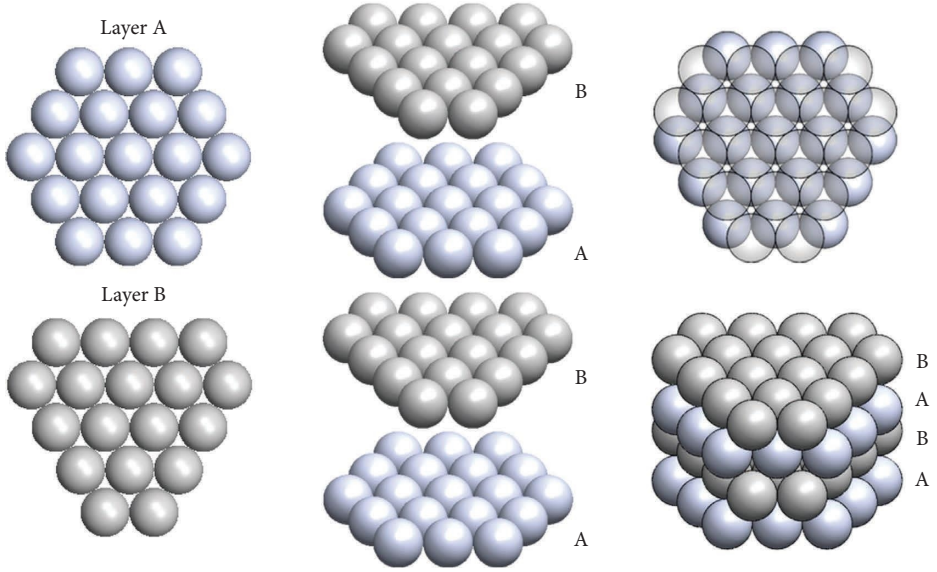

Figure 2: Multiple particle layer arrangement.

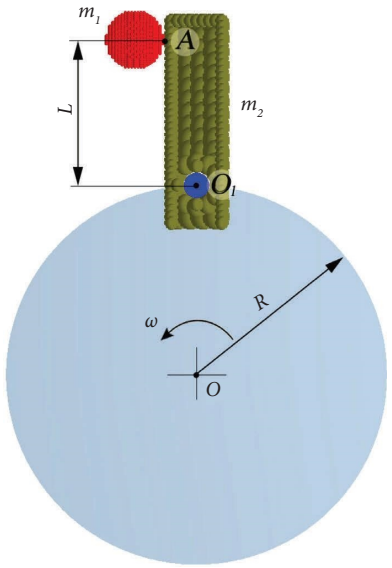

Figure 3: Collision model of the hammer crusher. m_1: agglomerate, m_2: hammer, ω: angular velocity of the rotor, L: distance from pivot O_1 to collision point A, and R: distance from the pivot of rotator O to that of hammer O_1.

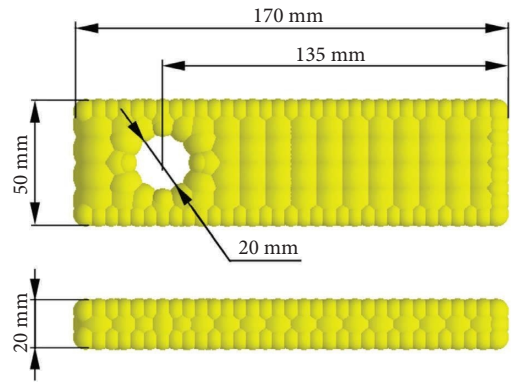

Figure 4: The hammer model making with spherical particles. This model is a particle shaped like the hammer.

pure elements has the same size of spherical particles, and it forms two types of structure, i.e., the hexagonal and cubic closest packing.

First, we make a first layer by distributing spherical particles into the nodes of a regular triangle lattice where the length of an edge is the same as the diameter of the spherical particle on the horizontal plane as shown in Figure 5(a), just the same as the mono distribution of Quist and Evertsson [19], resulting in gaps like △ and ▽ shapes between the spherical particles. One gap is formed surrounded by 3 spherical particles, with 6 gaps appearance around one particle. Then, we place the spherical particles on the gaps of either △ or ▽ shapes when making the second layer. Suppose that we might put the particles for making the 2nd layer on the △ shape gap just as shown in Figure 5(b), then the △ shape gaps on the first layer are hidden by the particles on the 2nd layer, while ▽ shape gaps on the 1st layer coincide with △ ones on the 2nd layer to turn into a ⬡ shape gap. There will appear 2 structures of hexagonal and cubic closest packing depending on how to make the 3rd layer. When substituting the 1st layer for the 3rd one, i.e., arranging 1st and 2nd layers, then 1st and 2nd layers, and further again, we can get the hexagonal closest packing structure with ⬡ shape gaps in the whole agglomerate as shown in Figure 5(b), just the same as the multiple particle layer arrangement of Jiménez-Herrera et al. [9]. In contrast, when again arranging the 1st, 2nd, and 3rd layers and further again after making a new 3rd layer by putting the spherical particles on the ⬡ gaps, we can obtain the cubic closest packing as shown in Figure 5(c). All the gaps are hidden in the cubic closest packing.

The spherical agglomerate models made from EDEM are shown in Figure 6. These agglomerate models are those bonded in weightless state by giving microproperties after arranging spherical particles of 3 mm in diameter according to the abovementioned hexagonal and cubic closest packing structures, in which agglomerates are 45 mm in diameter. The total numbers of particles are 2 493 and 2 491, respectively, and the total numbers of bonding between particles are 13 494 and 13 452, respectively. The packing efficiency is 0.74, and the coordination number is 12. The material of the spherical particles used is anthracite, whose density is 1,100 kg/m^3, Poisson's ratio is 0.36, and shear modulus is 0.51×10^3 MPa. Here, the density value is reduced to 1,485 kg/m^3 by considering the packing efficiency of the agglomerate model.

One of the major problems in completing the agglomerate model is to determine the microproperties (i.e., normal stiffness per unit area, shear stiffness per unit area, critical normal stress, critical shear stress, and bonded disk radius) of the model in accordance with the physical properties of materials of the object to be modeled. In this paper, this is achieved by back analysis. First, the drop impact experiments on the spherical anthracite samples were carried out and sieved, and the cumulative mass fractions of breakage products less than 1, 2, and 3 mm were measured. Then, the same models as the prototype experiments were built using EDEM, and the mass fractions of 1 mm, 2 mm, and 3 mm fragments were obtained by drop impact simulations. In this case, EDEM simulation should be carried out by establishing an experimental design with varying microproperties. Thus, EDEM simulation results should be used to establish the relationship between the mass fraction of the breakage product and the microproperties. Next, from EDEM simulation results, a nonlinear relationship between the mass fraction and the microproperties is established by MATLAB's "nftool" as an artificial neural network tool. Next, an optimization objective function is established to minimize the square deviation of the nonlinear relationship obtained by artificial neural network and the cumulative mass fraction of breakage products less than 1 mm, 2 mm, and 3 mm measured in real sample experiments, and then, the optimization solution is carried out by MATLAB's "optimtool (ga)" to determine the microproperties. The determined values are 8.5×10^8 N/m^3 of normal stiffness per unit area, 5.668×10^8 N/m^3 of shear stiffness per unit area, 4.999×10^7 Pa of critical normal stress, and 3.846×10^7 Pa of critical shear stress, and bonded disk radii are 0.12 mm, 0.141 mm, and 0.166 mm, respectively. At this time, the relative error between the results of the real sample experiments and EDEM simulation was less than 1.01%.

2.3. Simulation Result. The simulation results are given in Supplementary Materials. In addition, the following figures show the result of collision simulations on the above model where the diameter of agglomerate is 45 mm, the mass of the agglomerate is 0.057 kg, the mass of the hammer is 0.5 kg, and rotor speed is 750 r/min.

Figure 7 shows the velocity vector of particles on the center plan of the agglomerate according to time in the collision breakage process between the hammer and agglomerate. The velocity of particles is transformed along the crystal structure of the agglomerate from the collision point, and the greatest is the velocity of particles bursting into the vertical direction to beating face of the hammer from the center.

Figure 8 shows the characteristic curves according to time in the collision process. A new result in Figure 8(e) shows the energy change diagram of the hammer. It is obtained from the fact that the hammer is treated not as wall,

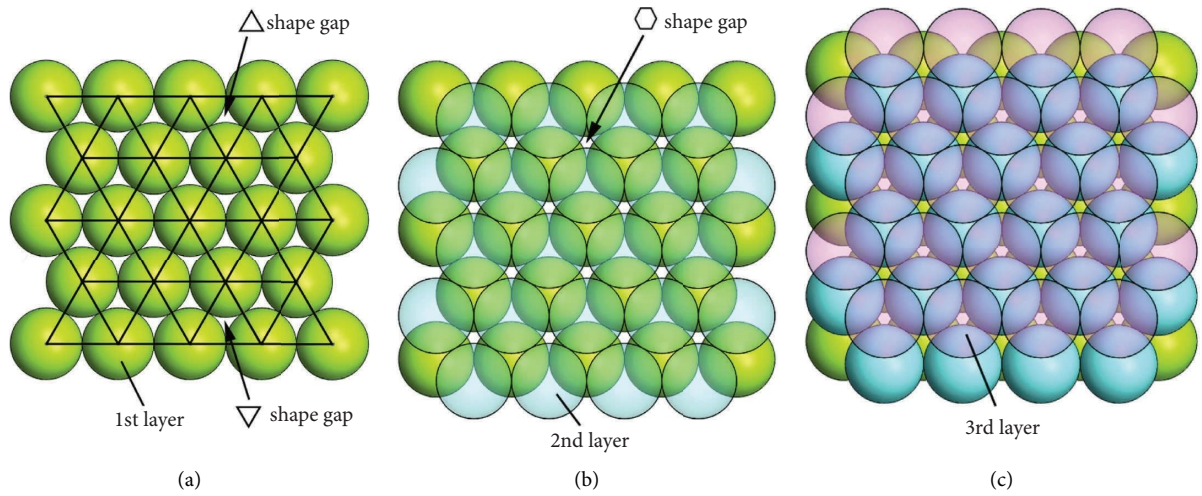

Figure 5: Method of crystal closest packing with spherical particles: (a) one-layer arrangement, (b) hexagonal closest packing, and (c) cubic closest packing.

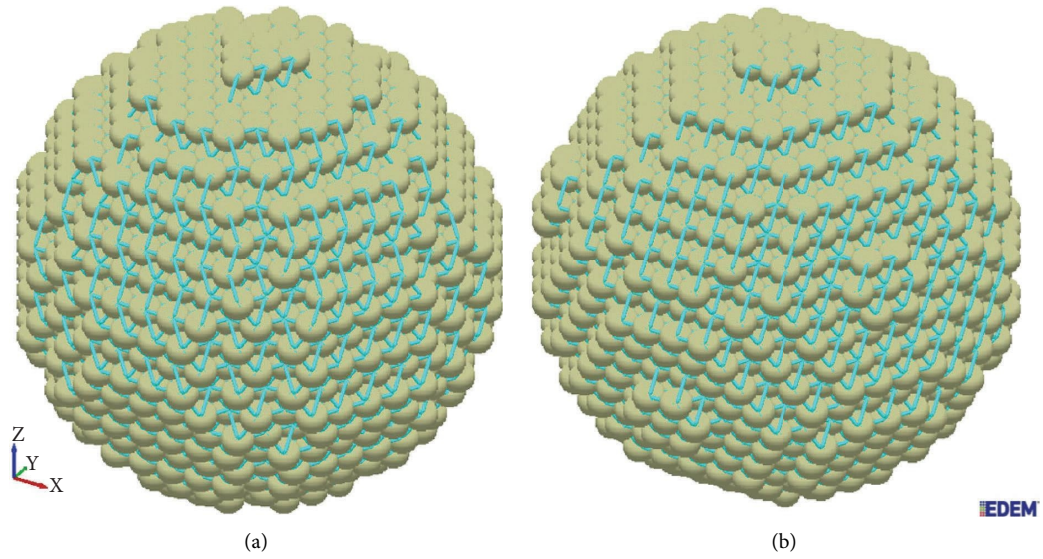

Figure 6: Spherical agglomerates with hexagonal: (a) cubic closest packing structures and (b) made in EDEM.

but as particle. From Figure 8, more correct collision breakage process between the hammer and agglomerate can be considered. Once the collision between the hammer and the agglomerate is started, the collision force is generated between the hammer and agglomerate. At this time, the velocity and energy of the hammer decrease, while those of the agglomerate's increase. It is because the energy of the hammer is transmitted into the agglomerate during the collision process. After a certain time passes (approx. 0.000 42 s) by, the collision force becomes zero; the velocity and energy of the hammer and agglomerate do not change but maintain constant values. This shows that the collision process is over. In the collision process, the energy loss quantity of the hammer is not equal to the energy increase one of the agglomerate. This is due to deformation and breakage of the agglomerate. In other words, it means that the energy difference (value of energy increase of the agglomerate subtracted from the loss energy of the hammer) is transformed into the breakage of the agglomerate.

Figure 9 shows the scale conversion of the maximum value of characteristic quantities 1 and minimum one as 0. This comparison curve clearly shows the interchanging relationship of characteristic quantities according to time. The velocity and energy are changed during the time of collision force existence. When the collision force becomes zero, the velocity and energy maintain the constant value, which coincides with Newton's law that motion is performed by force. But the rate of broken bonds of the agglomerate begins to increase from the range of the maximum collision force and approaches a certain limit value by increasing continuously even after it becomes zero. This explains that some of the energy transforming from the hammer to the agglomerate is saved as deformation energy, and then, it gradually converts to breaking the agglomerate.

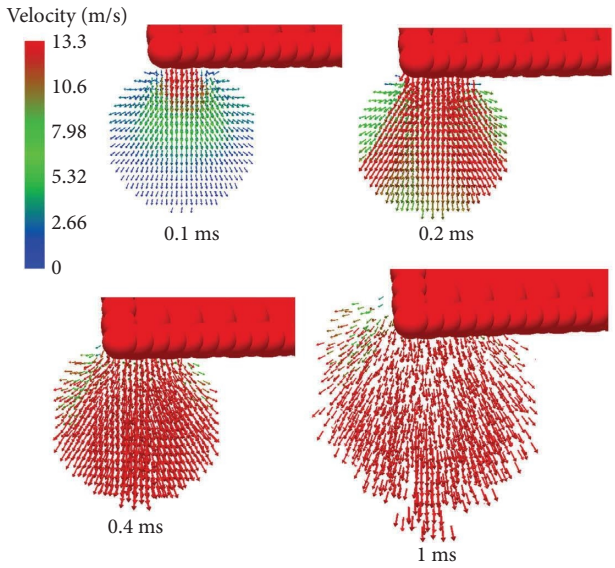

Figure 7: Velocity vector of particles from the collision point on the center plan of agglomerate. The velocity of particles is transformed along the crystal structure of the agglomerate from the collision point.

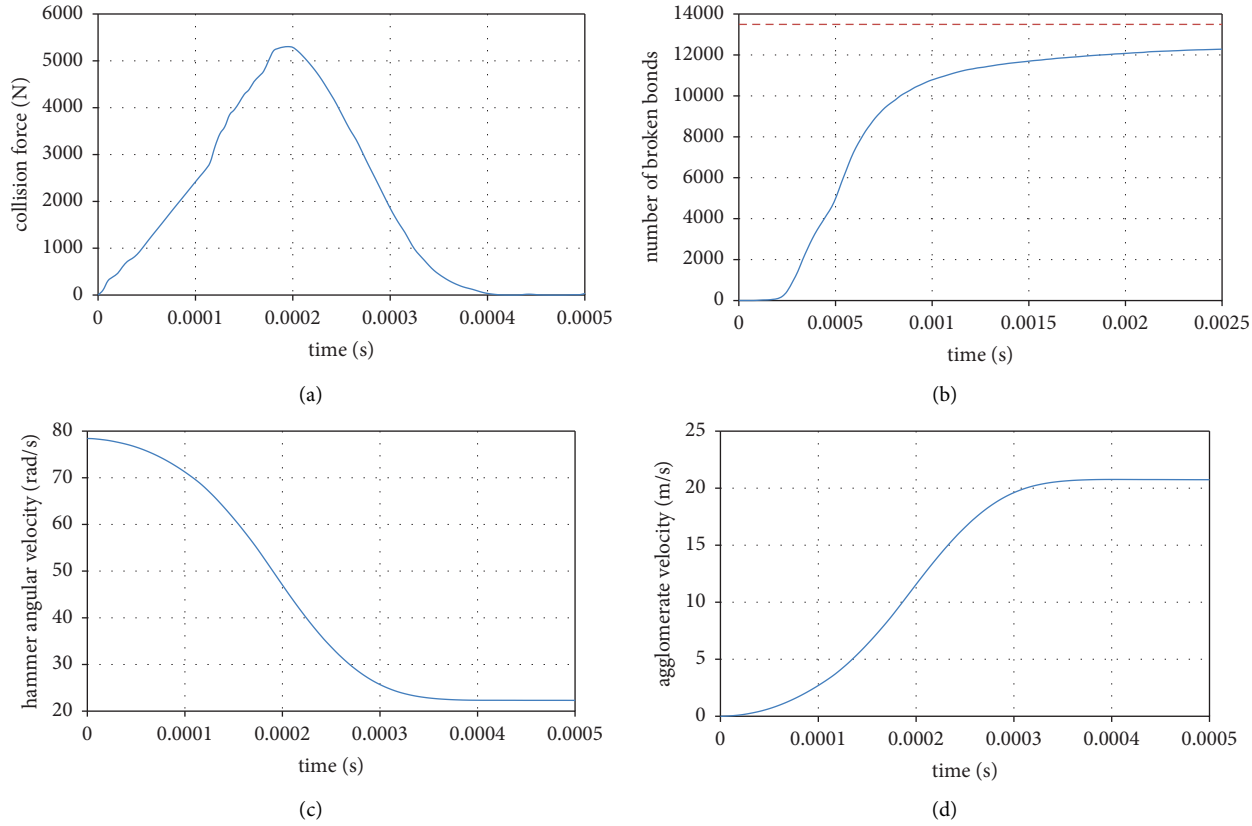

Figure 8: Continued.

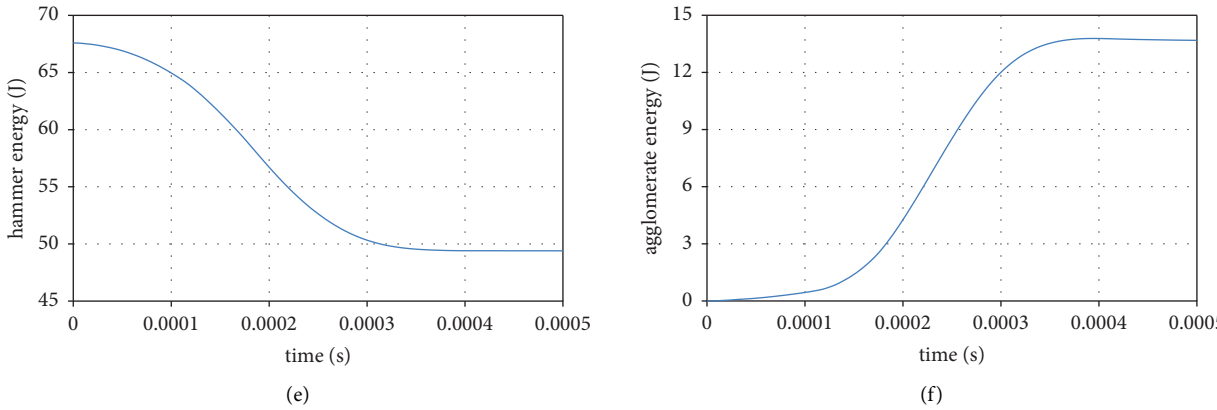

Figure 8: Changing curves of characteristic quantity according to the time collision breakage process: (a) collision force, (b) number of broken bonds of the agglomerate, (c) angular velocity of the hammer, (d) velocity of the agglomerate, (e) energy loss of the hammer, and (f) energy increase of the agglomerate.

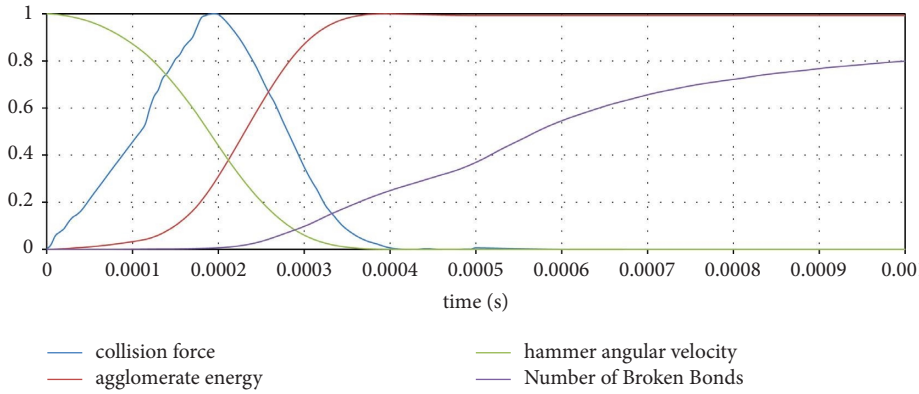

Figure 9: Scaling comparison result of each characteristic changes with time for curves a b, c, and f in Figure 8.

3. Discussion

3.1. Collision Force. As shown from the above simulation, the energy change takes place in the interval where the collision force exists as the mechanical motion is performed by force. Therefore, it is important to analyze the characteristics of collision force at first.

Figure 10 shows the change diagram of collision force according to time when impacting with a rotation speed of 1000 r/min and 500 r/min in simulation experiment results. The figure shows that collision force makes a certain cluster to change according to diameter (or mass) of agglomerate and rotating speed (or collision velocity) per minute; then, the maximum value/rate of collision force changes according to mass of the hammer in every cluster. But when the mass of the agglomerate approaches to that of the hammer (ratio of agglomerate mass over that of hammer is more than 0.5), the increasing effect of the hammer mass may bring or result in boundary destruction of clusters.

3.1.1. Treatment of Collision Force Simulation Result by Gaussian Function. Several qualitative analyses can be made in various viewpoints with the simulation result, but it is difficult to obtain its general law quantitatively due to complexity of the collision breakage process of the agglomerate. Thus, it is important to transform the simulation results into mathematic functions to ensure generality in every simulation experiment. From this viewpoint, Figure 8 shows that collision force change is mainly based on Gaussian function:

$$F(t) = a \bullet e^{-\left((t-b)^2/c^2\right)}. \quad (1)$$

Figure 11 shows the function regression by Gaussian function in case of 15 mm in agglomerate diameter, 1 kg in hammer mass, and 500 r/min in rotation speed and 75 mm in agglomerate diameter, 1 kg in hammer mass, and 1000 r/min in rotation speed. As shown in Figure 11, in two cases, every coefficient value of correlation R^2 is more than 0.99, so it can be said to reflect the well simulation result.

3.1.2. Collision Impulse. In equation (1), a is the maximum collision force and $2b$ is the collision time. Moreover, the collision impulse is obtained by the definite integral of Gaussian function in interval $[0, 2b]$:

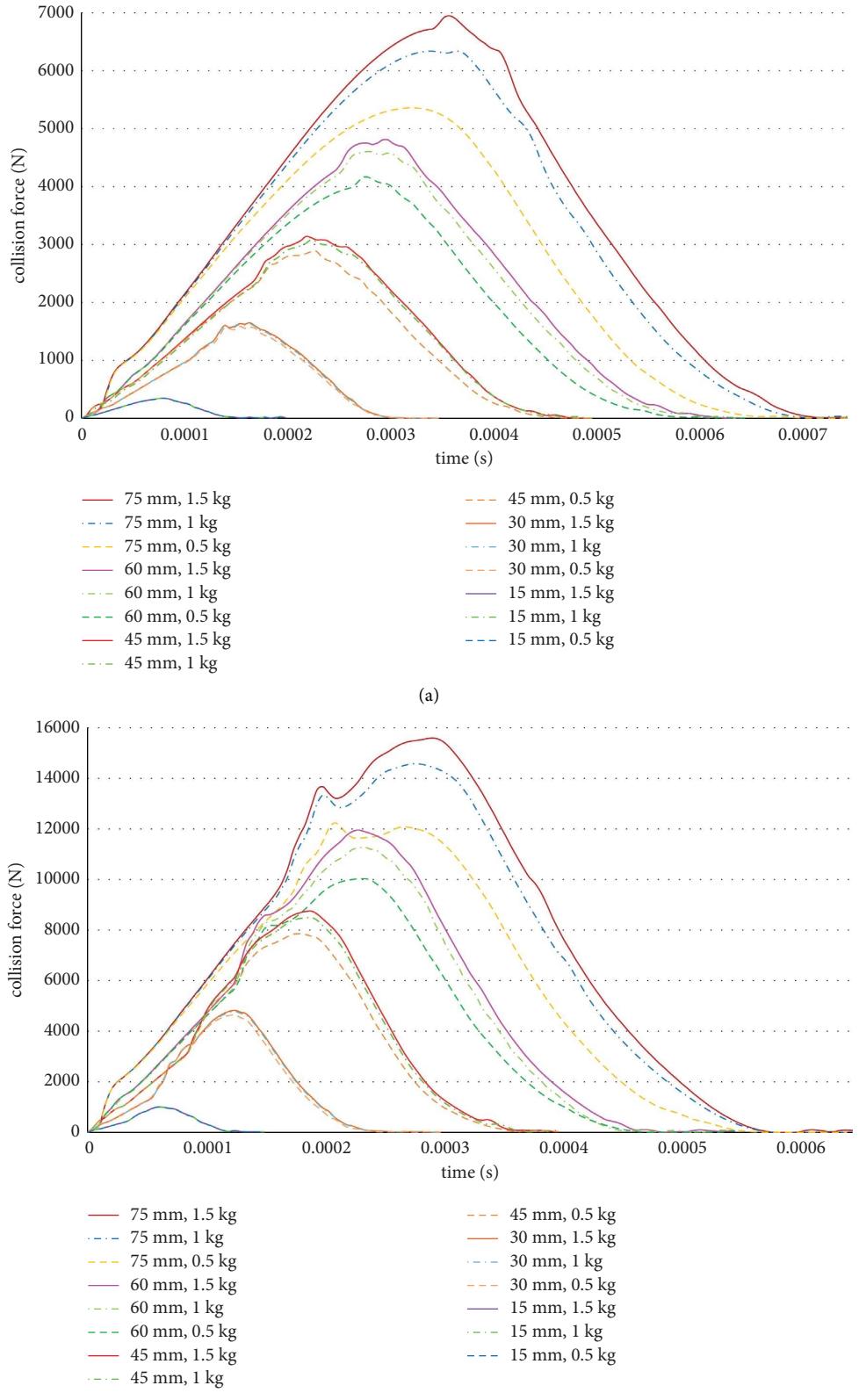

Figure 10: Collision force according to time: (a) when impacting with a rotation speed of 500 r/min ($v = 14.4$ m/s) and (b) when impacting with a rotation speed of 1000 r/min ($v = 28.8$ m/s).

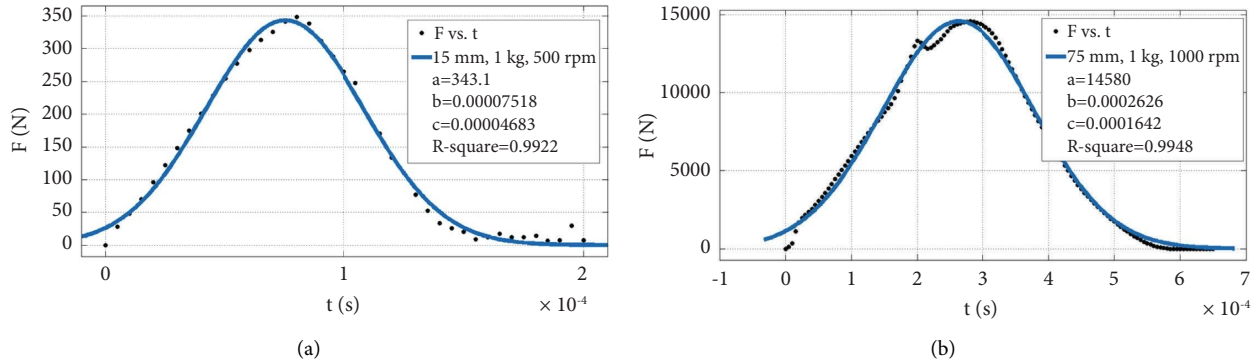

Figure 11: Fitting collision force by Gaussian function: (a) agglomerate diameter is 15 mm, hammer mass 1 kg, and rotation speed 500 r/min; (b) agglomerate diameter is 75 mm, hammer mass 1 kg, and rotation speed 1000 r/min.

$$S = a\int_0^{2b} e^{-\left((t-b)^2/c^2\right)}\mathrm{d}t \approx ac\sqrt{\pi},$$
$$\overline{F} = \frac{S}{2b}. \tag{2}$$

After converting the simulation results into equations (1) and (2), the variation of the collision impulse according to the collision velocity, agglomerate mass, and hammer mass is shown in Figure 12. This figure show that the collision impulse changes with a certain generality according to the agglomerate mass, hammer mass, and collision velocity. The collision impulse curves are very similar to linear increasing according to collision velocity and are similar to nonlinear increasing according to agglomerate mass. In addition, hammer mass has little influence on the collision impulse in small mass of the agglomerate but greater influence in greater mass of the agglomerate.

To find out a relationship of collision impulse, agglomerate mass, hammer mass, and collision velocity, the influence of agglomerate mass, hammer mass, collision velocity, and various assemblies of these factors on collision impulse is analyzed by the stepwise regression method (stepwise function of MATLAB). As a result, the conclusion can be drawn that the collision impulse S is the function of k_m and m_1v. Here, k_m is the ratio of agglomerate mass m_1 to hammer mass m_2 and m_1v is the product of agglomerate mass and collision velocity v:

$$S = f\left(k_m, m_1v\right),$$
$$k_m = \frac{m_1}{m_2}. \tag{3}$$

Hence, when performing function regression with k_m and m_1v as input data and S as output data, the following formula can be obtained. Here, the correlation coefficient is $R^2 = 0.998$, and its value does not increase more with the increasing degree of k_m:

$$S = km_1v,$$
$$k = \left(1.087 - 5.594\,k_m + 27.83\,k_m^2 - 65.66\,k_m^3 + 55.62\,k_m^4\right). \tag{4}$$

Collision impulse is the same as momentum change of a collided body. This simulation experiment shows that the initial velocity of the agglomerate is zero; thus, the product of k is expressed as multinomial k_m, and collision velocity v in equation (4) means the agglomerate velocity after colliding. This is coincident with the theory of collision. Then, when studying on collision phenomena of the rigid body in different conditions, the restitution coefficient is not said to be the proper property of the body but to be related to a collision condition. k expressed as multinomial k_m in equation (4) is a factor directly related to a restitution coefficient, and it shows that the restitution coefficient is also related to a collision condition.

3.2. Specific Breakage Energy and the Agglomerate Damage Ratio. One of the important purposes of studying the collision between the hammer and agglomerate by DEM is to predict the breakage energy consumed in crushers.

Similarly, for the collision impulse, the greater the agglomerate mass and collision velocity are, the greater the breakage energy of the agglomerate is, which is not greatly related to hammer mass. However, it can be seen that the nearer the agglomerate mass approaches to hammer mass, the greater the influence of the latter is. The breakage energy of the agglomerate is transformed by collision force generated when the agglomerate and hammer are colliding, so it is not reasonable to regard collision impulse and agglomerate mass as the reason of breakage energy.

Based on the above argument, when function regression is performed in the sequential regression method with a mass ratio of the agglomerate to collision impulse, agglomerate mass, and hammer mass as a variable, the breakage energy A_{break} is presented as the following equation with correlation coefficient $R^2 = 0.994$.

Equation (5) explains the breakage energy when collision impulse of S is generated by impacting against the agglomerate of m_1 in mass with the hammer of m_1/k_m in mass:

$$A_{\text{break}} = 8.667\,7\,S + \left(24.360\,2k_m - 60.457\,6\right)m_1. \tag{5}$$

When the hammer crusher is working, the energy of the motor is transferred to the hammer from the motor through the rotor. The energy transferred to the hammer through the

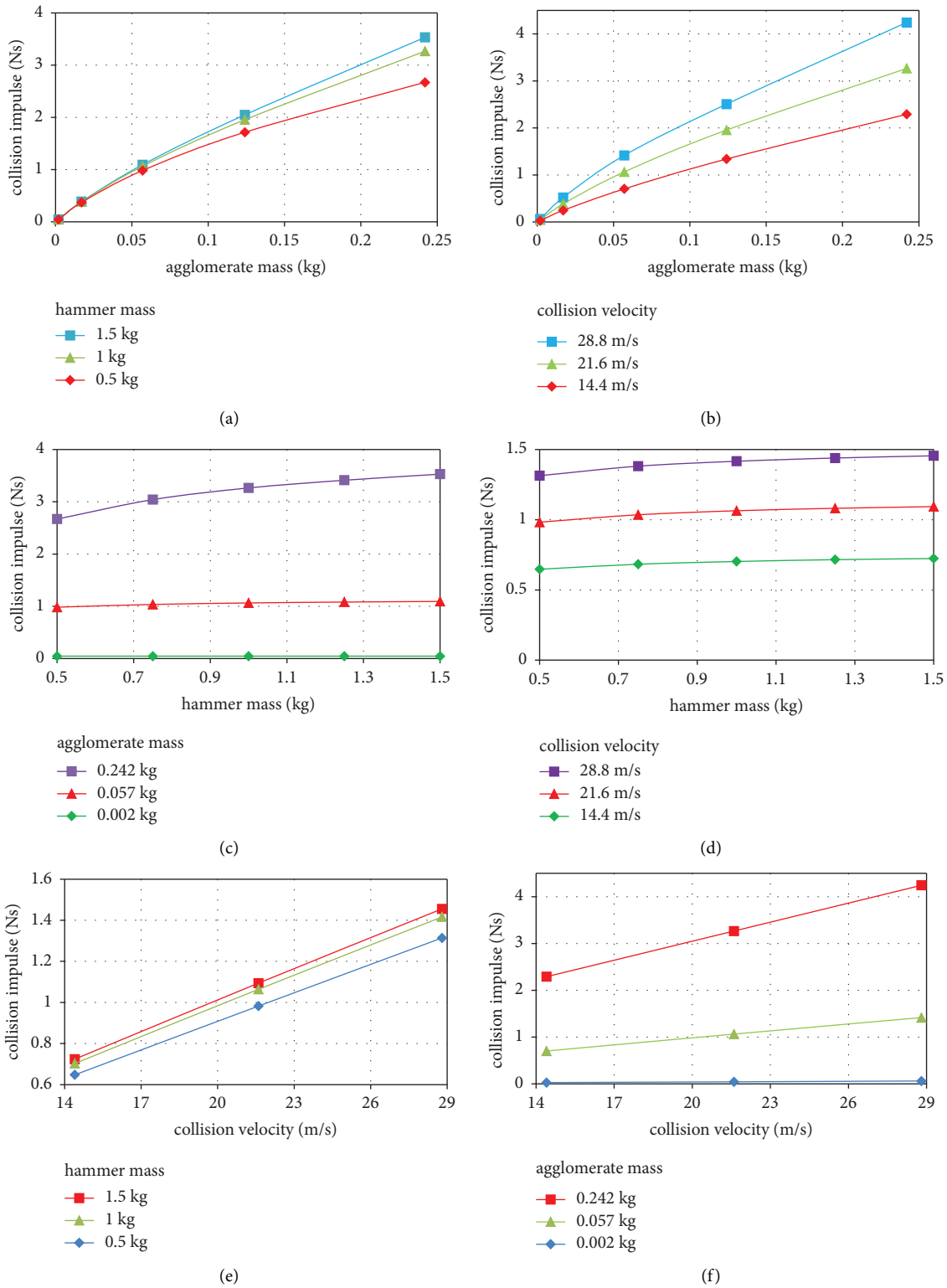

Figure 12: Change of collision impulse according to agglomerate mass, hammer mass, and collision velocity: (a) collision impulse curves according to agglomerate mass when collision velocity is 21.6 m/s. (b) Collision impulse curves according to agglomerate mass when hammer mass is 1 kg. (c) Collision impulse curves according to hammer mass when collision velocity is 21.6 m/s. (d) Collision impulse curves according to hammer mass when agglomerate mass is 0.057 kg. (e) Collision impulse curves according to collision velocity when agglomerate mass is 0.057 kg. (f) Collision impulse curves according to collision velocity when hammer mass is 1 kg.

Table 1: Agglomerate damage ratio evaluated by particles of 3 mm in diameter.

Hammer mass (kg)	Rotation speed of rotor (r/min)	Specific breakage energy (J/kg)	Damage ratio (%)
0.5	500	34.311	78.32
	625	53.595	83.03
	750	76.872	86.98
	875	104.88	89.86
	1000	138.68	91.67
	1125	177.70	93.27
	1250	222.45	94.65
1	500	39.075	79.89
	625	60.618	84.47
	750	87.17	88.43
	875	119.40	91.08
	1000	158.42	92.49
	1125	202.15	94.24
	1250	252.91	95.10
1.5	500	40.844	80.42
	625	63.35	84.93
	750	91.181	88.58
	875	125.02	91.31
	1000	165.71	92.91
	1125	211.75	94.36
	1250	265.78	95.20

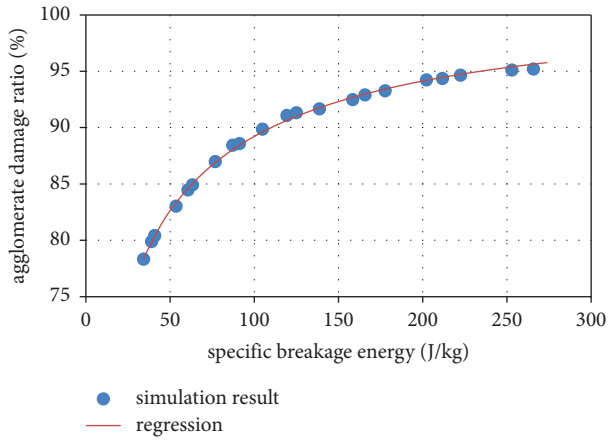

Figure 13: Relationship between specific breakage energy and agglomerate damage ratio.

rotator from the motor during the working process in the hammer crusher supplements the energy lost in the collision breakage process by using the hammer so as to ensure its normal work. The breakage energy efficiency η_1 when the agglomerate is broken in the hammer crusher is, therefore, defined as the ratio of the breakage energy of the agglomerate to the energy loss of the hammer in the hammer crusher:

$$\eta_1 = \frac{A_{\text{break}}}{A_{\text{hammer•loss}}}. \tag{6}$$

One of the important indexes in evaluating the breakage effects in impact crushers is to evaluate the relationship between the specific breakage energy a_m and the agglomerate damage ratio p_b. The specific breakage energy a_m and the agglomerate damage ratio p_b are represented by following equations:

$$a_m = \frac{A}{m},$$
$$p_b = \frac{nb_2}{nb_1} \bullet 100, \%. \tag{7}$$

Here, A is the breakage energy consumed in breaking the agglomerate, m is the agglomerate mass, nb_1 is the number of bonds between particles before breakage, and nb_2 is the number of broken bonds after breakage.

The damage ratio of the agglomerate is an index that can be measured in the study on breakage by DEM. Since it is impossible to measure the damage ratio of the agglomerate in a general method in a breakage experiment on real agglomerate, the cumulative mass fraction has been employed to estimate the breakage product. However, this, being a scale index for the size

distribution of breakage product, does not reflect energy. For example, suppose that the amount of breakage product of less than 1 mm takes up 50%, we cannot expect how much energy is consumed here and how much energy will be more needed for breaking agglomerate completely less than 1 mm in the future. Since the damage ratio that can be calculated by DEM simulation is the percent of the number of broken bonds after breakage over the number of bonds between particles forming the agglomerate before breakage, it indicates a really-broken degree with the particle size forming the agglomerate as standard.

When the specific breakage energy is zero, the agglomerate damage ratio is zero, and the agglomerate damage ratio increases according to the increasing specific breakage energy, thus finally reaching 100% when the bonds between particles are all broken. Thus, the relationship between specific breakage energy a_m and the agglomerate damage ratio p_b can be represented by using exponential function.

On the other hand, the agglomerate damage ratio and the size distribution of the crushed product can be considered to have correlation as indexes evaluating the breakage degree of materials. The Rosin–Rammler distribution obtained by observing the size distribution of the crushed product in the hammer crusher by Dey et al. [4] is also an exponential function. From this viewpoint, when function regression is performed in the form of exponential function by using simulation results of this paper, the following equations can be obtained. Here, the agglomerate damage ratio is evaluated by particles of 3 mm in diameter as standard, assuming that the crushed product less than 3 mm in the hammer crusher can be obtained:

$$p_b = 100\left\{1 - \exp\left[-\left(0.4482 a_m^{0.3481}\right)\right]\right\},$$
$$a_m = \exp\left\{\frac{1}{0.3481}\ln\left[\frac{1}{0.4482}\ln\left(\frac{100}{100 - p_b}\right)\right]\right\}. \quad (8)$$

Table 1 shows the simulation results obtained by carrying out the collision breakage simulation between the hammer and agglomerate by changing the hammer mass to 0.5, 1, and 1.5 kg and changing the rotor rotational speed to 500, 625, 750, 875, 1000, 1125, and 1250 r/min. Figure 13 shows the function regression results based on the data in Table 1.

As shown in Table 1 and Figure 13, it can be seen that the hammer mass is not considered to have influence on the relationship between the specific breakage energy and the agglomerate damage ratio. In addition, it shows that the requested specific breakage energy according to the agglomerate damage ratio increases exponentially; thus, much larger breakage energy may be consumed to get a large damage ratio at a time. Consequently, we found that when the damage rate is 85%, the required specific breakage energy is 63 J/kg, and when the damage rate is 90%, it is 110 J/kg, which increases 1.75 times, but when the damage rate is 95%, it increases 2.13 times as high as 234 J/kg.

4. Conclusion

In this paper, the collision breakage process between the hammer and the agglomerate in the hammer crusher was investigated by DEM simulation to obtain the collision force, the collision impulse, the breakage energy of agglomerate, and the relationship between the specific breakage energy and the agglomerate damage ratio. Of particular importance is the ability to capture the energy loss of the hammer during collision breaking.

One of the major objectives of studying the breakage process of agglomerates in crushers including the hammer crusher is to predict the energy required for breakage works by considering the energy change relationship of breaking tools. The simulation bodies in DEM contain the particle and wall. Here, the particle has mass and energy, but the wall does not have mass, so energy cannot be discussed. Although DEM has been widely used in the research of powder engineering and has achieved many successes, the energy change of the breaking tool could not be considered because the breaking tools, such as hammers, were modeled as the wall in previous studies that investigated the breakage process using DEM. However, in our study, the hammer was made into a particle model with a combination of particles rather than walls, in accordance with the nature of the DEM, in order to obtain the energy change in the hammer. This method allows the prediction of the energy to be added to the breaking tool to break the agglomerate by directly measuring the energy loss of the breaking tool in the study on the breakage process by DEM.

In order to study the breakage process in DEM, it is necessary to build an agglomerate model by bonding the particles. In this paper, from the viewpoint of attaching greater importance to internal structure rather than the external one of the breakage process in agglomerate modeling, an agglomerate model is made starting from one perspective on internal crystal structure of minerals discussed in crystal mineralogy. This method ensures the packing efficiency of 0.74 by closest packing of the particles that constitute the agglomerate. This value is very large compared to the previous methods and is the maximum value that can be achieved when agglomerate is made of particles of the same size.

Using the hammer and agglomerate models, in this paper, the collision breakage process between them was simulated and the breakage pattern of the agglomerate was analyzed. Also, it was found that the shape of the collision force is similar to the Gaussian function and concluded that the collision impulse is a function of the ratio of the agglomerate mass to the hammer mass and the product of the agglomerate mass and the collision velocity. Importantly, the energy change of the hammer and the agglomerate during collision breaking was measured to obtain the breakage energy and the loss energy of the hammer. Also, the relationship between the specific breakage energy and the agglomerate damage ratio in the hammer crusher was found to be an exponential function.

We believe that the proposed method could be extended to various types of crusher to assist in the design of crushers and needs further development.

Data Availability

The data used to support the findings of this study are included within Supplementary Materials.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was financially supported by the National Science and Technical Development Foundation of DPR Korea (Grant no. 24-20210501). Also, the authors thank Prof. Il Yong Kang for insightful reviews on an earlier version of this article.

Supplementary Materials

A table in Supplementary Materials shows the collision simulation results. (*Supplementary Materials*)

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