Powder Technology 318 (2017) 543–548

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

A combined experimental and DEM approach to determine the breakage of particles in an impact mill

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ARTICLE INFO

Article history:
Received 23 March 2017
Received in revised form 6 June 2017
Accepted 11 June 2017
Available online 13 June 2017

Keywords:
Grinding
Population balance model
Discrete element method
Selection function
Breakage function

ABSTRACT

Population balance models (PBMs) are widely used to predict particle size variation in grinding. An accurate determination of particle breakage and selection functions in PBMs requires detailed knowledge on the stress causing particle breakage. This study proposed a combined experimental and numerical approach to determine the two functions. In the physical experiments, the breakage of individual iron ore particles in a Fritsch impact mill with different mill speeds was investigated and the product sizes were analysed. The simulations based on the discrete element method (DEM) were carried out under similar conditions to examine the dynamics of the particles inside the mill, such as number of impacts, impact velocity and impact angle. The simulation results showed that most of the particles experienced multiple impacts before they were ejected from the mill. The first impacts occurred at low impact energy which had no contribution to particle breakage. The second and third impacts, on the other hand, posed high impact energy on the particles and were the main cause of particle breakage. Based on the simulation results and the experimental data, two semi-empirical selection and breakage functions were determined. The accuracy of the equations was confirmed by applying them to predicting the size distribution of ground particles under different mill conditions.

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1. Introduction

Population balance model (PBM) has been widely used to predict the variation of product size in grinding of particles [1–3]. It incorporates a breakage rate function that describes the rate that material breaks out of each size class with an appearance (or breakage) function – the average size distribution of the progeny from each breakage event. It provides a powerful approach to investigate industrial grinding devices, which allows developing a uniform model that describes the operating behaviour of rod, ball, semi-autogenous and autogenous mills. PBM has been demonstrated to provide a much superior prediction of grinding performance than the empirical Bond work index model.

A main obstacle to apply PBM to grinding is the determination of the two parameters in the model, namely breakage and selection functions. Often the functions are determined experimentally for various materials by conducting single particle breakage test under well-defined stressing conditions [4], such as air-gun [5,6], drop tests [7–10], compression [11–13], pendulum test [14,15] and rotary impact tester [16,17]. In experiments, single particle is broken and splits into fragments when an external force stronger than the particle strength acting on it. Therefore, particle strength, external force acting on the particle and fragment size distribution after the particle breakage can be considered as the three main aspects of the single particle breakage. These methods allow for a systematic investigation of the particle breakage behaviour independently from mill related features.

Recently Vogel and Peukert [16,17] used a modified commercial lab-scale mill (Fritsch) to conduct single particle breakage test. They also proposed a breakage model based on Rumpf's theory and Weibull model to fit the results. Compared to other single particle breakage facilities, the device is easy to set up, can be operated continuously and has a capability of grinding a wide range of materials and particle sizes with minimum material loss during experiments. So it can be an ideal device to determine particle selection and breakage functions. However, because the detailed impact condition inside the mill was lacking, the fitting of the functions was based on the assumptions that all the particles had only one impact with the mill and the impact velocity and impact angle are the same with a given mill speed. However, these assumptions have never been tested. As the assumptions are critical to the fitting of the functions, they should be carefully examined based on the particle dynamics.

This work is to combine experiments and numerical modelling to tackle this issue. Numerical simulations based on the discrete element method (DEM) are used to reveal the impact conditions of the particles

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http://dx.doi.org/10.1016/j.powtec.2017.06.026
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while the experiments are to obtain the particle size distribution. The aim is to develop a method which is able to determine the breakage and selection functions more accurately.

2. Methodology and conditions

2.1. Physical experiments

In the experiments, the breakage of individual iron ore particles was investigated using a Fritsch PULVERISETTE 14 rotor mill, as shown in Fig. 1. There have been several studies to determine the breakage of single particles using various devices. While the approach in the current study can be applied to other single particle tests, there are no enough experimental details in order to make quantitative comparison. Fritsch mill is a convenient and easy operation device for research single breakage, so it has been selected for this study. The mill consists of a feeding funnel, an impact rotor with 12 ribs and a collection pan. In the experiments, the mill was operated at a given speed, and the particles were fed to the mill one-by-one through the funnel. Accelerated by the centrifugal force, the particles moved outward and impacted against the ribs, causing particle breakage. In the experiments, the mill was operated without a sieve to avoid unbroken particles being retained inside the rotor [16,17]. When the particles left the rotor, they were collected by the collection pan. After the test, the sizes of the collected particles were analysed using the sieving method. In each test, around 100 g of iron ore particles ranging from 2.36 mm to 3.15 mm were fed into the mill. The mill speed was varied from 6000 rpm to 14,000 rpm (corresponding to the velocity of the ribs from 23 to 53.5 m/s) to examine its effect. 3 tests were conducted for each speed to ensure the reproducibility and accuracy of the results.

2.2. DEM simulation

Simulations under the conditions similar to the experiments were conducted using an in-house developed DEM model [18,19]. The motions of individual particles are traced by explicit numerical solution of Newton's equation of motion [20]. For particle i, its translational and rotational motions are determined by:

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \left(\mathbf{F}_{n,ij} + \mathbf{F}_{t,ij}\right) + m_i\mathbf{g} \tag{1}$$

and

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j \left(\mathbf{R}_{ij} \times \mathbf{F}_{t,ij} - \mu_r R_i \left|\mathbf{F}_{n,ij}\right| \hat{\boldsymbol{\omega}}_i\right) \tag{2}$$

where $\mathbf{v}_i$, $\boldsymbol{\omega}_i$, m_i and I_i are the translational and angular velocities, and mass and moment of inertia of particle i, respectively; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{R}_{ij}$ is the vector pointing from the centre of particle i to its contact point with particle j; $\mathbf{F}_{n,ij}$ and $\mathbf{F}_{t,ij}$ are respectively the normal and tangential contact forces from particle j to particle I; and the summation is over all particles contacting with particle i.

Based on the simplified Hertz-Mindlin and Deresiewicz model, the normal and tangential forces are given by [21,22]:

$$\mathbf{F}_{n,ij} = \left(-\frac{4}{3}E^*\sqrt{R^*}\delta_n{}^{3/2} - c_n\left(8m^*E^*\left(R^*\delta_n\right)^{1/2}\right)^{1/2}\left(\mathbf{v}_{ij}\cdot\hat{\mathbf{n}}\right)\right)\hat{\mathbf{n}} \tag{3}$$

$$\begin{aligned}\mathbf{F}_{t,ij} = \Big(&-\mu_s\left|\mathbf{F}_{n,ij}\right|\left(1-\left(1-\delta_t/\delta_{t,\max}\right)^{3/2}\right) \\ &-2c_t\left(1.5m^*\mu_s\mathbf{F}_{n,ij}\left(1-\delta_t/\delta_{t,\max}\right)^{1/2}/\delta_{t,\max}\right)^{1/2}\mathbf{v}_{t,ij}\Big)\,\hat{\boldsymbol{\tau}}\end{aligned} \tag{4}$$

where $E^* = \frac{Y}{2(1-\tilde{\sigma}^2)}$, Y is Young's modulus and $\tilde{\sigma}$ is the Poisson's ratio; c_n and c_t are the normal and tangential damping coefficients respectively; $R^* = R_iR_j/(R_i + R_j)$ and $m^* = m_im_j/(m_i + m_j)$; δ_n is the normal displacement; $\mathbf{v}_{ij}$ is the relative velocity of particle j to i; $\hat{\mathbf{n}}$ is the normal vector of the contact plane; μ_s is the sliding friction coefficient; δ_t is the total tangential displacement during contact; $\delta_{t,\max} = \mu_s[(2-\tilde{\sigma})/2(1-\tilde{\sigma})]\delta_n$, $\mathbf{v}_{t,ij}$ is the relative velocity of particle j to i along the tangential direction; and $\hat{\boldsymbol{\tau}}$ is the unit vector of tangential direction. The second term of the torque in Eq. (2) results from the rolling resistance between two contacting particles due to elastic hysteretic losses or viscous dissipation, where μ_r is the rolling friction coefficient and $\hat{\boldsymbol{\omega}}_i = \boldsymbol{\omega}_i/|\boldsymbol{\omega}_i|$ [22]. The particle-wall interactions can be calculated according to the same equations, with the radius of a wall being assumed to be infinitely large. Table 1 lists some parameters of the particles.

Fig. 2a shows a simplified mill device in the simulations, which consist of a fixed top disc and a rotating rotor with 12 ribs. A simulation started with the random generation of a particle in the feeding zone (centre of the top disc). The particle fell down under gravity, moved outwards when it contacted with the rotor and impacted with the ribs. The process was repeated so in total 100 particles were fed one by one with no interactions with each other. The simulations were conducted with various mill speeds. Fig. 2b shows the representative trajectory of a

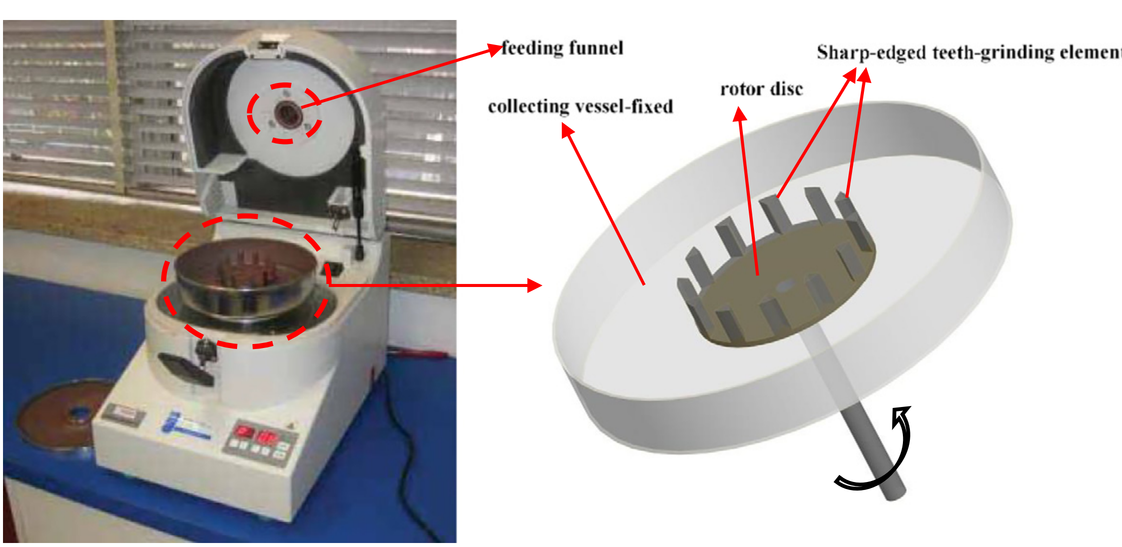

Fig. 1. Details of the impact mill used in the experiments.

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