Analysis on Grinding media Motion in Ball Mill by Discrete Element Method

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Abstract: -Based on the research on the grinding media motion in the ball mill, the discrete equation of grinding media motion about ball mill is established and the motion regimes of grinding media is simulated using the discrete element method (DEM) with simplifying the contact model of grinding media and rock material. Comparing and analyzed the simulation results, such as motion regimes and motion trajectory of the grinding media, the discrete equation is verified. Under the method mentioned, the analysis of the relationship between grinding media motion and grinding efficiency could be got and thus some information and reference could be gained from this work.

Key-words: - Discrete Eelement Method (DEM)， Ball mill， Grinding media motion， Simulation

1 Introduction

Ball mills are extensively used in mining, construction, metallurgy, chemistry, power, etc. However, the motion state of practical charge (material and grinding media) is too complicated to be described precisely. Previous research work deal with the media motion can be divided into two categories: These are the behavior of single grinding media or a certain grinding media[1] and the behavior of the center of the entire charge which was considered as a rigid object.[2] Since the former ignored some factors such as the size and shape of particles will cause error between theoretic simulations and experiments, it is difficult to establish a comprehensive motion equation. Meanwhile the latter was lack of representing the media motion and interactions.

Firstly DEM(*Discrete Eelement Method*) is adopted to simulate the grinding media motion in a ball mill. Under a distinguished numerical method with broad prospect, DEM have been developed increasingly to solve discrete media problems recently. Compared to traditional methods, DEM not only reduces horal and economical costs, but also it has large capability to receive data that are difficult to be detected or measured in experiments. Therefore, present theories of ball mill have been improved to solve actual problems .Under the method, the goal of optimized design of ball mill could be achieved.

DEM regards discrete objects as a set of finite discrete particles. Then the charge could be abstracted as a group of particles which are isolated, contacting and interacted by each other[3]. The DEM cycle of computing procedure of particle motion state is shown in Fig.1.

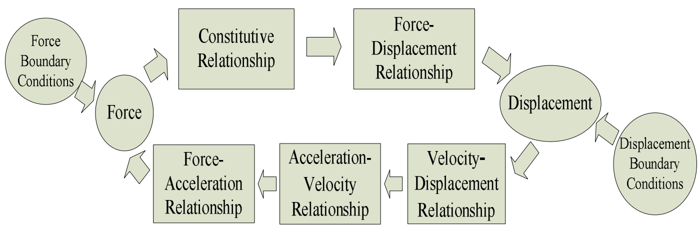
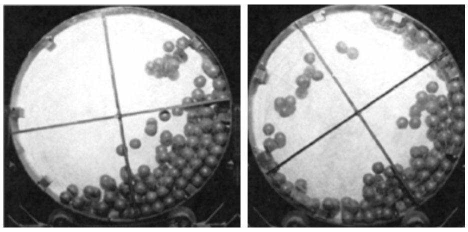


Fig. 1 DEM Cycle Computing Procedure

2 Description and Hypothesis of Media Motion

It is the grinding media motion to generates the grinding effect. Normally there are two types of motion patterns that are cascading and cataracting[4]. When grinding media are moving in cascading, media move up with the mill shell till a certain height and then fall down along the surface of charge ramp. Rock material is grinded in the procedure of the media up-rolling and down-rolling. While media tumble down to the bottom of the mill, partial impact the toe region, but the primary grinding effect is produced by slight impact in cascading.

On the other hand, under the circumstance of cataracting, after media rose to that height, they could be a projectile in a trajectory. During the trajectory falling, there is no relative movement between grinding media and rock materials for their falling at the same velocity. However, the impact of charge hitting the toe will be much stronger than what was mentioned above. In cataracting, shocking plays large impact while grinding is much less effective. As shown in Fig.2 media motion state was captured by high-speed camera [5].



(a) cascading (b) cataracting

Fig. 2 Media motion captured by high-speed camera

Therefore, There are some features of the grinding media motion in a mill as following:

- Tumbling and movements of media are driven by mill shell. Impact and tumbling occur between media and mill shell.
- The particle motion is independent each other while locomotive connection exists due to the particles contacting other particles and material around them.
- Effect of grinding occurs between grinding media and materials.

In order to simulate the grinding media motion by DEM , several hypotheses should be made:

- Grinding media is considered as *rigid bodies*. Actually media is usually made by steel which can be regarded as rigid
- The assumption that particle contact happen in a small scale is presented, namely the particle contact in *point contact.*

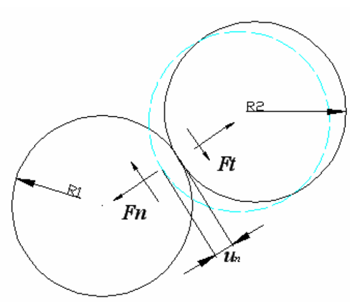


Fig.3 Particle contact model

3 DEM Formulation of Grinding Media Motion

3.1 Contact Model of Grinding Media

Grinding particles, including grinding media and rock materials, roll with the grinding shell achieving the grinding effect. The force analysis of grinding media is crucial for the contact model to analysis media motion. Grinding media (such as steel balls) are modeled as individual smooth round spheres and illustrated in Fig.3. R_1 and R_2 are two contacting ball radiuses. Virtual overlap is allowed at the contact point. The contact forces include the normal force F_n which is vertical with contact interface and tangential force F_t which is parallel to the contact interface. F_n can be determined:

$$F_n = k_n * \mu_n \tag{1}$$

where k_n is the normal stiffness at the contact point and μ_n is the relative contact displacement in the normal direction (overlapping between balls).

Contact force of particle follows the friction law of Coulomb[6], and the shear force can be calculated by the following formula:

$$\left.\begin{array}{l} F_t = k_t * u_t ---\left(|F_t| \le F^s_{\max} = \mu |F_n|\right) \\ F_t = \mu * |F_n| ---\left(|F_t| > F^s_{\max} = \mu |F_n|\right) \end{array}\right\} \tag{2}$$

where μ is the friction coefficient; k_t is the normal stiffness at the contact point ; μ_t is the shear displacement and $F^s_{\max}$ is the maximum frictional force.

3.2 Discretization of Media Motion Equation

The motion states of grinding media are determined by unbalance force and unbalance moment in the ball mill. The performance of movement consist of "revolution"(rotation around the centre of the cross-section of the mill) and “rotation”(rotation around the centre of grinding media itself), as shown in Fig.4.

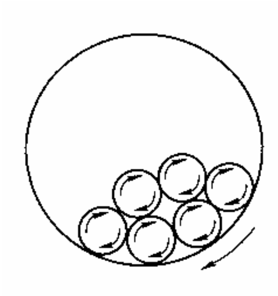


Fig.4 “Revolution” and “Rotation” of grinding media

In the DEM model, media is effected by gravity and multiple contact forces respectively, as can be described as following：

$$\begin{cases} f_x - \mu v_x = m\dfrac{dv_x}{dt} \\ f_y - \mu v_y = m\dfrac{dv_y}{dt} \\ f_z - \mu v_z = m\dfrac{dv_z}{dt} \end{cases} \quad (3)$$

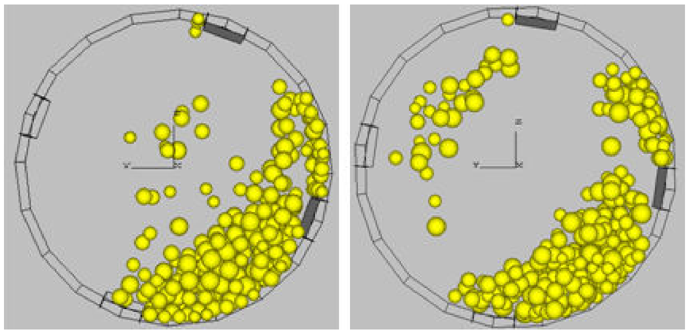
$$\begin{cases} M_x - \mu\omega_x = I\dfrac{d\varpi_x}{dt} \\ M_y - \mu\omega_y = I\dfrac{d\varpi_y}{dt} \\ M_z - \mu\omega_z = I\dfrac{d\varpi_z}{dt} \end{cases} \quad (4)$$

where m is the mass of grinding media particle element; f_x 、f_y、f_z represent the resultant forces of unbalance forces in x、y、z axis direction; M_x、M_y、M_z represent the resultant moments in x、y、z axis direction; ϖ_x、ω_y、ω_z represent the angular velocity components in x、y、z axis direction; I is the moment of inertia.

Equation of grinding media motion is discretized by using central difference method:

$$\begin{cases} \dfrac{dv_i}{dt} = \dfrac{v_i^{(t+\Delta t/2)} - v_i^{(t-\Delta t/2)}}{\Delta t} \\ \dfrac{d\varpi_i}{dt} = \dfrac{\varpi_i^{(t+\Delta t/2)} - \varpi_i^{(t-\Delta t/2)}}{\Delta t} \end{cases} \quad (5)$$

Eq. (5) substituted into Eq. (3) and (4), thus v_i 、 ϖ_i are represented as following:



(a) Cascading (b) Ctaracting

Fig.5 DEM Model Of Media Motion State

$$\begin{cases} v_i^{(t+\Delta t/2)} = v_i^{(t-\Delta t/2)} + \dfrac{f_i - \mu v_i}{m} * \Delta t \\ \varpi_i^{(t+\Delta t/2)} = \varpi_i^{(t-\Delta t/2)} + \dfrac{M_i - \mu\varpi_i}{I} * \Delta t \end{cases} \quad (6)$$

where v_i、ϖ_i represent respectively the velocity component and angular velocity component of grinding media particle element in different directions ($i = x, y$˜Az).

Due to the force generated by displacement, the force-displacement is calculated within the same time-step and the cycle calculation process is shown in Fig.1. According to Eq. (6), new speed and new angular velocity can be computed. Thus new location of grinding media is updated as following:

$$\begin{cases} x^{(t+\Delta t/2)} = x^{(t)} + v_x^{(t+\Delta t/2)} \bullet \Delta t \\ y^{(t+\Delta t/2)} = y^{(t)} + v_y^{(t+\Delta t/2)} \bullet \Delta t \\ z^{(t+\Delta t/2)} = z^{(t)} + v_z^{(t+\Delta t/2)} \bullet \Delta t \end{cases} \quad (7)$$

$$\begin{cases} \theta_x^{(t+\Delta t/2)} = \theta_x^{(t)} + \varpi_x^{(t+\Delta t/2)} \bullet \Delta t \\ \theta_y^{(t+\Delta t/2)} = \theta_y^{(t)} + \varpi_y^{(t+\Delta t/2)} \bullet \Delta t \\ \theta_z^{(t+\Delta t/2)} = \theta_z^{(t)} + \varpi_z^{(t+\Delta t/2)} \bullet \Delta t \end{cases} \quad (8)$$

Where θ_i is the rotation quantity of grinding media around its axis and x、y、z is the coordinate components of grinding media centroid.

Under what mentioned above, both the new locations of grinding media and the new contact forces will be worked out. The resultant forces and resultant moments will promote grinding media to get acceleration and angle acceleration, so the velocity and displacement of media are obtained by integral of entire incremental time-step. This cycle will not stop until the specified time is coming.

4 DEM model of media motion

Here the simulation of the grinding media motion in the ball mill is performed by both 2D and 3D DEM software package particle flow code (PFC) from Itasca. PFC consider the basic mechanical properties of medium based on the view of medium elementary particles structure and model the movement and interaction of assemblies of arbitrarily-sized circular (2D) or spherical (3D) particles.

4.1 Model of media motion states

According to the geometric parameters of ball mill and the contact parameters between particles, the program is compiled and merged to simulation software. Then the simulation model of ball mill shell is established. The rotating velocity of the mill in cascading or cataracting is determined and import to software. The different states of media motion can be analyzed by PFC model as shown in Fig.5.

Comparing with the motion states figure of laboratory ball mill, the analysis of simulation results were recorded by a high-speed camera(Fig.2), it can be found that the DEM simulation results were similar to the actual motion state of grinding media and different zone of grinding media motion can be clearly distinguished. It is shown by the present studies that DEM is suitable for solving microcosmic problems, such as the comminution of particles, the relationship between particles fracture and energy consumption ,etc.

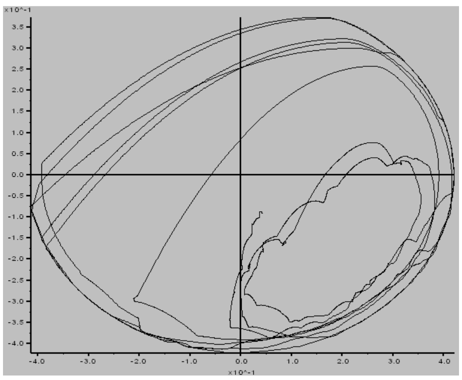


Fig.6 DEM Model Of Particle Trajectory

4.2 DEM model of media trajectory

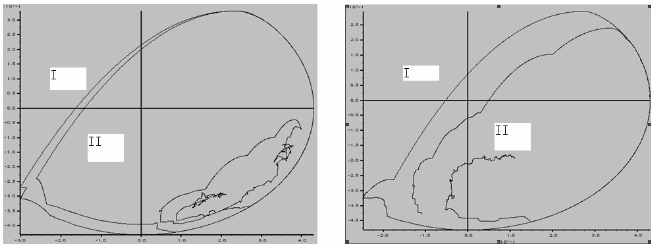
Media on the liners are lifted up to a certain height and then released by gravity as shown in Fig.6. The simulation results of grinding media trajectory by DEM present the motion situation of grinding media and record massive dates, such as the position of the release height and the falling point of grinding media. When grinding media are lifted up by liners in the shell, media are getting potential and kinetic energy , then collision between grinding media and particles will happen and the energy of media which are major source of material grinding will be released while grinding media falling.

There are many factors effect the motion states of grinding media, especially mill filling level is more important. While mill filling low, there isn't collision happened between grinding media before media come to contact with the liners at the bottom of mill shell. But on the other hand, while mill filling high, there is collision happened between grinding media during the falling of grinding media. The effect of collision and friction is turning particles to smaller. The above conclusion is verified by analyzing motion trajectories of grinding media under different mill filling levels as shown in Fig.7.In Fig.7(a), motion trajectory curves I˝AII of grinding media are smooth. It demonstrates that there is no collision happening. In Fig.7(b), some significant mutations appear in motion trajectory curves II of grinding media demonstrates that collision occur between grinding media in fall process and change motion trajectory of grinding media. In order to raise grinding rate of rock materiel in the ball mill, it is necessary to select a definite mill filling level.

5 Conclusions

Considering significantly infl. uences of motion state of the grinding media to the grinding efficiency, here the theoretically analysis and simulation of media motion study on how mill filling affects media motion by DEM.

The method not only benefit to solve the shortcomings of traditional research methods, such as limitations of particular mill size and particle amount etc., but also it is great helpful to replace some difficulty experiments, especially those experimental data is hard to measure in the laboratory mill. So it is useful to predict the abrasion of grinding media and the power draw with the improvement of computer hardware and numerical technology.



(a) low mill filling (b)high mill filling

1.7 motion trajectory of grinding media under different mill filling level

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