Estimation of Liner Design in a Tube Mill by Discrete Element Method*

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Tube mills having four kinds of liner designs (MODEL I, II, III and IV) were modelled to evaluate the effect of liner design on the impact energy by the Discrete Element Method (DEM). The ball charge motion was simulated, and the impact energy of balls was calculated. The charge motions of MODEL I (duolift), III (step wave) and IV (lifter liner) were cataracting and cascading, and motion in MODEL II (steps) seemed to be cascading under the condition of \( N/N_C = 0.72 \) (\( N_C \): critical rotational speed). MODEL I, III and IV gave larger impact energy than that of MODEL O (without liner). MODEL III had the largest \( E_n \) (normal component of impact energy) in all mills; and it was 32% superior to MODEL O. The distribution of \( E_n \) shifts to high-energy range when the mill had liner. The effective area for the grinding in MODEL I, III and IV were around toe of ball charge due to cataracting motion. Therefore, the grinding performance will be improved by the liner, especially design of MODEL III is the best according to this analysis.

KEY WORDS: Discrete Element Method, Impact energy, Tube mill, Computer simulation, Liner

1. Introduction

Many industries have large-scale ball mills in grinding processes because the ball milling is one of the easiest methods for producing powder, and size reduction is, of course, one of the most important unit operations. For example, in a cement production process, the grinding is taken in initial and final stages. The raw materials of limestone, hematite and silica solids are ground in a tube mill at the initial stage, and cement clinker, which is produced by calcinations in a rotary kiln, is also ground with gypsum to produce the final product. It has been reported that about 100 kWh of electricity must be needed to produce 1.0 ton of cement, and more than 60% of total electricity is consumed in the grinding process [1]. The wear of balls is another serious problem; e.g. it was reported that the consumption of balls is 850 g/day [2]. Therefore, it is important to grind materials with high grinding efficiency, and optimisation of ball milling is necessary.

Most of tube mills have liner on the inner mill wall as lifter in order to increase the grinding efficiency, and ball charge motion is sensitive to the shape of liner [3]. There are several investigations into the tube milling [4-6], and analysis of tumbling ball milling by using a computational simulation based on the Discrete Element Method (DEM) [7-10] had been developed. The ball charge motion with considering presence of powder was simulated by Authors [11]. The effect of presence of powder in a ball mill was considered by frictional coefficient, which was obtained by an angle of repose of powder sample. The authors had proposed the impact energy which was calculated from the relative velocity on the collision, and the correlation between the grinding rate in the experimental work and the specific impact energy of balls was found out [12]. This relationship was given by a straight line, regardless of grinding conditions; e.g. mill scale [13], ball-filling [14], ball size [15] or ground materials [16]. The specific impact energy is also useful for the designing of the planetary ball mill. The pot rotational direction and speed ratio between pot and disk rotations were optimised by the impact energy, [17] and the scale-up method of the planetary ball mill was proposed [18]. Therefore, this impact energy has a high potential to estimate the grinding performance in an industry-scale tube mill. The tube mill in cement industry has liner on the inner mill wall, and there are several liner designs. People want to know the effect of the liner shape on the grinding performance, however each mill has some compartment with different liner shape, and the type of classifier is also different. Thus, it is quite difficult to evaluate the effect of the liner design on the grinding performance.

In this paper, the modelling of the liner in the tube mill was conducted by DEM. Ball charge motions in five tube mills having different shapes of liner design; i.e. MODEL I (duolift), II (steps), III (step wave) and IV (lifter liner), and O (without liner) are simulated. The impact energy per unit time was calculated to derive the effect of liner design.

2. Simulation

2.1 Discrete Element Method

Three-dimensional ball charge motion in the tube mill was simulated by DEM [19]. Voigt model [20] was used for the contact model, and the contact forces (\( F_n \): compressive force, \( F_s \): shear force) were calculated from following equations.

\[ \text{Equation} \]
Where, \( K \) and \( \eta \) mean a spring and a damping coefficients. \( u \) and \( \phi \) are the relative displacement of the gravitational center between two balls and the relative angular displacement, \( r \) is the radius of ball. \( E \), \( \nu \) and \( e \) are Young's modulus, Poisson's ratio and restitution coefficient, respectively. The subscript \( n \) and \( t \) denote the normal and tangential components. The translational and rotational motions of each ball are updated by following equations.

\[
F_n = K_n \frac{\Delta u_n}{\Delta t} + \eta_n \frac{\Delta u_n}{\Delta t} \tag{1}
\]

\[
F_t = \min \left\{ \mu F_n, K_t \frac{\Delta u_t}{\Delta t} + \eta_t \frac{\Delta u_t}{\Delta t} \right\} \tag{2}
\]

\[
K_n = \frac{4}{3\pi} \left( \frac{1}{\delta_n + \delta_f} \right) \frac{r_f}{r_n + r_f} \tag{3}
\]

\[
K_t = \frac{K_n}{2(1+\nu)} \tag{4}
\]

\[
\delta_i = \frac{1}{E \rho} \frac{r^2}{r_f} \tag{5}
\]

\[
\eta = 2\gamma \sqrt{\rho m} \tag{6}
\]

\[
\gamma = \frac{\ln \epsilon}{\sqrt{\pi^2 + 1n^2 \epsilon}} \tag{7}
\]

\[
\frac{1}{m} = \frac{1}{m_i} + \frac{1}{m_f} \tag{8}
\]

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\[
\dot{\mathbf{v}} = \frac{\sum F}{m} + \mathbf{g} \tag{9}
\]

\[
\dot{\omega} = \frac{\sum M}{I} \tag{10}
\]

Where, \( \mathbf{v} \) is a vector of ball velocity, \( F \) is the summed force acting on a ball, \( m \) and \( \mathbf{g} \) mean the mass of a ball and 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.

2.2 Modelling of liner shapes

Four liner designs in tube mills were modelled to derive the effect of liner shape on the impact energy. The inner diameter of a tube mill was 3.5 m, which was similar to the actual mill in the cement industry, and its length was shortened to 0.7 m in order to reduce a calculation time. MODEL I had a wavy liner, and Fig. 1(a) shows the snapshot of cross section of this liner. There were two kinds of convexity between the concavities. The liner shape of MODEL II was step liner as shown in Fig. 1(b). MODEL III (Fig. 1(c)) had wavy shape on step liner. MODEL IV was the trapezoidal liner (Fig. 1(d)). The mill without liner (MODEL O) was also simulated to compare with those mills. The total number of lifters was set constant at 28, and the rotating direction of the mill was clockwise in all mills.

2.3 Simulation condition

The material properties of mill wall and balls were used ones of steel, and coefficient of friction was determined as 0.77 by the angle of repose of clinker powder (11). Balls having 60, 70, 80 or 90 mm in diameter were mixed and charged into each mill; its total ball-filling ratio to mill volume was about 30%. The detailed physical properties are tabulated in Table 1. The relative rotational speed, \( N/N_C \) (\( N_C \): critical rotational speed, 22.6 rpm) was changed from 0.4 to 0.85.

2.4 Impact energy

The impact energy of balls was calculated to evaluate the liner design. It has been already reported that this impact energy correlates with the grinding rate constant in ball milling under various grinding conditions (12-16), and the relationship between the specific impact energy and the grinding rate constant is linear. Therefore, the grinding rate can be predicted and milling performance is estimated by calculating the impact energy. The impact energy is defined by the relative velocity on a collision, \( \mathbf{v}_r \), which consists of a normal, \( \mathbf{v}_N \), and tangential component, \( \mathbf{v}_T \), as given by Equation (11).

\[
E = \frac{1}{2} M \mathbf{v}_r^2 \tag{11}
\]

\[
M = \frac{2m_i m_j}{m_i + m_j} \tag{12}
\]

\[
\mathbf{v}_r^2 = \mathbf{v}_N^2 + \mathbf{v}_T^2 \tag{13}
\]

The impact energy is summed for every collision during the simulation time, and the impact energy per unit time is...
obtained by Equation (14), where $t_s$ is total simulation time.

$$E_i = \frac{\sum \sum E}{t_s} \tag{14}$$

### 3. Results and Discussions

Fig. 2 shows the snapshots of a cross section of ball charge motion in tube mills having different liners under $N/N_C = 0.72$. Different colours of balls designate ball size. The ball charge motion in MODEL I, III and IV are cataracting and cascading, motion in MODEL II and O seem to be cascading. It is found that the lifter helps balls to be raised up in the mill.

Fig. 3 shows the impact energy of balls per unit time, $E_i$. $E_i$ of MODEL I, III and IV are superior to MODEL O. MODEL II produces $E_i$ nearly the same value of MODEL O. Table 2 shows the relative impact energy to the value of MODEL O ($=100$). The normal impact energy, $E_n$, was calculated from the normal component of the relative velocity and the tangential impact energy, $E_t$, was calculated from tangential one. The total impact energy is improved about 7% except for MODEL II. It is found that $E_n$ of MODEL III is 32% greater than that of MODEL O, 4% superior to MODEL IV and 9% to MODEL I. On the other hand, $E_t$ of all mills are similar value or less than MODEL O because the slipping ball on the mill wall is reduced by the existence of liner. These improved impact energies are effective for the grinding because the energy efficiency of the grinding has seemed as below 1% and huge amount of electricity is consumed in the grinding process. Therefore, a few percentages of improvement of the impact energy are noteworthy.

Fig. 4 shows the distribution of $E_n$ for all mills under $N/N_C = 0.72$. The distributions of mills having liner shift to high-energy range, and those of MODEL I, III and IV can have larger normal impact energy spectrum as

![Fig. 2 Snapshots of cross section of ball charge motion.](image)
comparing with MODEL II and O. The value of impact energy on each collision becomes large when the mill has complicated design of liner. The liner makes large impact energy not only total amount of normal impact energy but also each impact. The impact energy fields of $E_n$ for five mills are mapped in Fig. 5, colours are changed along with the value of impact energy. It is found that the collisions near mill wall have small impact energy because balls move with the wall rotation. The most effective grinding areas in MODEL I, III and IV are different from those of MODEL O and II. The mills of MODEL I, III and IV have the large impact energy area around toe to the middle of the balls flow surface due to cataracting and cascading motions, on the other hand, the large energy areas for MODEL O and II are middle of flow surface due to cascading. Therefore, it is concluded that having the liner on mill inner surface is worthy for carrying balls and leads to large impact energy and improvement of grinding efficiency. The shape of the liner is also one of the important factors for efficient grinding, and MODEL III would be the most effective under $N/N_C = 0.72$.

Fig. 6 shows the relation between the impact energy (Fig.6(a): $E_n$, Fig.6(b): $E_t$) and the relative rotational speed with a parameter of liner shape. The impact energy increases with an increasing the rotational speed, and $E_n$ became large especially $N/N_C = 0.85$, on the other hand, $E_t$ for $N/N_C = 0.85$ are similar to those of $N/N_C = 0.72$ when mills have liner. This means that the ball charge motion became the cataracting motion in MODEL I, II, III and IV. Fig. 7 shows the distribution of $E_n$ for MODEL III with a parameter of rotational speed. The distributions shift to high-energy range with increasing the rotational speed due to cataracting motion. The large impact energy will be useful for the grinding, however it concerns wear of balls and mill wall. So that, the wear and the power consumption should be discussed with the impact energy for the optimisation of tube milling, and it will be possible in the future.

4. Conclusions

In this paper, four kinds of liner designs of a tube mill
The existence of the liner in a tube mill can produce large impact energies on each collision according to the impact energy distribution curves. There is large difference between the distribution curves of five mills, especially MODEL I, III and IV have large impact energy spectra.

4. The large impact energy area in MODEL O and II are at the middle of the flow surface due to the cascading motion, however, those of MODEL I, III and IV are around toe to the middle of flow surface.

5. The normal component of impact energy increases with increasing the rotational speed, and the motions of mills having liners became cataracting under $N/N_C = 0.85$. The distribution of normal impact energy shift to high-energy range with increasing the speed. The large impact energy will be useful for the grinding, however it concerns wear of balls and mill wall. Thus the rotational speed should be controlled at suitable condition.

6. Ball milling simulation by DEM is an effective method for the evaluation of liner design in tube mill. The optimisation of milling operation will be possible by considering the power consumption and wear of liner and balls in the future.

**References**

離散要素法によるチューブミル内ライナー形状の評価

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DEM（Discrete Element Method, 離散要素法）を用いたボールミルシミュレーションにより、チューブミル内ライナー形状の評価を行った。4種類（モデルI～IV）のライナーをモデル化し、ボール運動挙動をコンピュータシミュレーションにより再現し、衝突エネルギーを算出した。モデルI（duolift）、III（step wave）、およびIV（lifter）では、ボール挙動はキャタラクティングとカスケイディングであり、一方、モデルII（step）ではカスカデイングであった。また、モデルI, III, IVにおけるボール間衝突エネルギーは、ライナーを持たないミル（モデルO）よりも増加し、粉砕性能が向上することがわかった。また、どのライナーにおいても、衝突エネルギーの法線成分は著しく増加し、ライナーを持つことで衝撃による粉砕が強くなる。また、1回当たりの衝突エネルギーも大きくなり、ミル内の高衝突エネルギー域も、ライナー形状が複雑になるに従って、ミル壁近傍になることがわかった。以上のことより、チューブミル内にライナーを導入することにより、粉砕性能が上昇し、また、ライナーデザインはモデルIIIのような複雑な形状の方が良いことがわかった。

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