DEM Investigation of Mill Speed and Lifter Face Angle on Charge Behavior in Ball Mills

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Abstract. Discrete element method (DEM) was used to study the effect of mill speed and lifter face angle on the characteristics of charge group. Based on the bin algorithm, a position density limit is proposed to study the motion of the charge. The result shows that the angle of charge group is mainly affected by mill speed and the measured result proves that the predicted equation is reasonable.

1. Introduction

Ball mill has been extensively used in mineral, cement and chemical industries [1-3]. However, there is a problem of high-energy consumption and low efficiency in the milling process. Mill speed and lifter are the prime importance in the efficiency of comminution in ball mills, which seriously affect the charge motion. Characterization on the charge motion is one of the most important requirements for analyzing the performance of the mill. The charge motion cannot be effectively controlled, which will lead to the increases of the invalid impact and unwanted particle size distribution. Therefore, it is essential to have a good understanding of the mechanics of the charge motion.

To date, scholars have done a lot of researches on the kinematics of charge. Among these, Powell [4] summarized the definition of the characteristic region of charge motion, and analyzed the charge motion to improve milling efficiency. Morrell [5] studied the effect of mill speed, lifter shape and filling on the shape of load in a laboratory mill. Cleary [6] systemically studied the effects of changes in mill operating parameters and particle properties on the charge shape and power draw of a ball mill. Mishra [7] used a laboratory-scale mill to analyze the charge dynamics in tumbling mills by vibration signature technique. Maleki-Moghadam [8] developed a software called Grinding Media Trajectory (GMT) to predict the shape and trajectory of charge in industrial mills. Above all mainly focused on the charge motion in simulation and experimental method [9-12], which provides a theoretical basis for the design ball mills. However, there has always been a problem of the lower measurement accuracy.

A DEM model of ball mill (Ø520×40 mm) was established. Based on discrete element meshing method, a charge position density limit model is proposed to analyze the variation of the charge behavior under different mill speed and lifter face angle.
2. Materials and methods

2.1. The model mill
To understand the effect of mill speed and lifter face angle on charge kinetics, a model mill with an internal diameter of 520 mm and axial length of 40 mm is used in the present study, and equipped with 24 pieces of trapezoidal lifter equally spaced. The model mill filled by iron ore (non-spherical particle) and grinding media (steel balls). Main characteristics of the simulation parameters are listed in Table 1.

Table 1. Simulation parameters

| Parameters                        | Values               |
|-----------------------------------|----------------------|
| Steel ball size (mm)              | 10                   |
| Iron ore size (mm)                | 5.92×6.02×4.33       |
| Steel ball density (kg·m⁻³)       | 7800                 |
| Iron ore density (kg·m⁻³)         | 3886                 |
| Lifter height (mm)                | 12                   |
| Lifter base width (mm)            | 20                   |
| Steel ball filling                | 25%                  |
| Iron ore filling                  | 10%                  |
| Mill speed (of critical speed)    | 55%,70%,85%          |
| Lifter face angle (from lifter face) | 15°,25°,35°       |
| Steel ball shear modulus (Pa)     | 7×10¹⁰               |
| Iron ore shear modulus (Pa)       | 2.6×10⁹              |

2.2. Description of charge motion
The identification of unique features of the charge allows the charge motion to be characterized. These definitions are considered by Powell and Nurick work, which aimed to better characterize the structure of the charge. In this paper, the analysis was based on the DEM simulation and the description of charge motion are shown in Figure 1.

Figure 1. Description of charge motion

- **Head**: Apex of charge trajectory
- **Shoulder**: Region where charge depart from shell and enter free fall
- **Centre of circulation**: Point about which all charge in mill circulates
- **Bulk toe**: Point of intersection of tumbling charge with mill shell
- **Impact toe**: Region where impacting charge imparts shell or bulk charge
3. Results and discussions

3.1. Charge position density limit

Snapshot images of the charge are of limited usefulness when characterizing the charge motion. To statistically describe the charge motion, the charge position density limit is generated using a 100×100 cells, where each cell represents a bin. The bin algorithm allows the frequency of any measured variable to be expressed as a function of position within the mill. The bin plots of the charge position density limit are shown in Figure 2. The color of each grid area represents the number of charge where it’s located. The darker the color, the greater the probability density of the charge.

Figure 2 shows the shape of charge group predicted for the model mill. Increasing the mill speed results in kidney-like region diffusion, charge position density limit gradually dispersed. For 55% of critical speed, a few cataracting charge impacts the bulk charge in the broken region, most of the charge flows down the steep free surface into the broken region. At 70% of critical speed, the

Figure 2. Charge position density limit
The shoulder angle was the point where the charge depart from the mill shell and enter free fall. From Figure 3(a), it is clear that the shoulder angle increases with increasing mill speed at any given lifter face angle. However, the shoulder angle decreases with increasing lifter face angle at any given mill speed. The impact toe was assumed to be the point where cataracting charge impacts the mill shell or bulk charge. As shown in Figure 3 (b), the impact toe angle was inversely proportional to mill speed, but proportional to lifter face angle. The bulk toe was the point of intersection of cascading charge
with mill shell. In Figure 3(c), increasing mill speed results in bulk toe angle increases, but increasing lifter face angle results in bulk toe decreases.

Based on the influence of lifter face angle and mill speed on angle of shoulder, impact toe and bulk toe, a mathematical equation is established to predict the angle.

\[
\theta_s = -0.24\alpha + 0.97\varphi - 3.42 \\
\theta_i = 0.74\alpha - 2.29\varphi + 353.84 \\
\theta_b = -0.06\alpha + 0.29\varphi + 217.78
\]

where $\theta_s$ is the shoulder angle; $\theta_i$ is the impact toe angle; $\theta_b$ is the bulk toe angle; $\alpha$ is the lifter face angle; and $\varphi$ is the mill speed.

It can be seen from the above predicted equation affected that the slope of the angle to the mill speed increases obviously, while the slope to the lifter face angle decreases. In order to verify the accuracy of the equation, the predicted values of the angle are calculated and compared with their measured values. The results are shown in Figure 4, the predicted values of the angle are basically the same as those of the measured values. Thus, the predicted equation is reasonable. Based on the predicted equation, the position of the angle of shoulder, impact toe and bulk toe can be determined quickly and simply, which lays a data foundation for the further analysis of the dynamics of charge group.

![Figure 4](image-url)
4. Conclusion
(a) Based on the bin algorithm, a position density limit is proposed to study the motion of the charge.
(b) Though the photograph of charge position density limit, the characteristics of charge group are investigated. The result shows that the angle of charge group is mainly affected by mill speed. Additionally, the mathematical equation of angle is constructed, the result shows that the angle of charge group is mainly affected by mill speed and the measured result proves that the predicted equation is reasonable.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (grant No. 51475458), the Program for Changjiang Scholars and Innovative Research Team in University (grant No. IRT_16R68). The authors also wish to thank the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD) and the Top-notch Academic Programs Project of Jiangsu Higher Education Institutions (TATP).

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