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A method to predict shape and trajectory of charge in industrial mills

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ABSTRACT

Charge motion is of prime importance in the efficiency of comminution in tumbling mills. Since direct observation of charge shape and its motion in industrial mills are not possible, a combination of analytical and physical studies was used to determine charge trajectory. Software packages, which predict charge motion such as the GMT (Grinding Media Trajectory) only consider the outermost layer of charge (single ball) and ignore the charge and the interactions of grinding elements. In this research, the charge trajectory measured in a laboratory mill (model mill) with the diameter of 100 cm and length of 21.5 cm with the transparent end was compared with that of the GMT. Three types of polyurethane rings were accurately machined to scale down the liners arrangements at two industrial mills. To explore various charge shapes and trajectories, the model mills were operated at 55%, 70% and 85% of critical speed for five levels of mill filling (10%, 15%, 20%, 25% and 30% by volume). The special design of the model mill which enabled gradual increase of the mill length so as to minimize the impact of the end-wall effect. The experiments indicated that the ends wall effect was negligible for the model mill with the length of 10.8 cm and beyond. The proposed relationships to correct the trajectory and charge shape obtained by the GMT were validated by using the new liner of the Gol-E-Gohar iron ore company AG mill. The average relative error of prediction was found to be 1%. The results indicated that when the lifter face angle increased from 7° to 30°, the distance between the charge impact point and the toe decreased from 40.1° to 11.2° for 30% filling. This meant increasing the probability of charge impacting the toe not the liner which favoured more efficient comminution practice. After converting AG mills to SAG mills on the account of liner profile change, 31% increase in throughput (from 419 to 548 t/h) in addition to 4% decrease in the product size (from 516 to 496 μm) were realized which was a significant contribution to the plant performance improvement.

1. Introduction

Comminution is the most energy intensive operation which constitutes the major portion of operating and capital costs of the mineral processing plants. Due to inherent complexity of the grinding a comprehensive model to describe the process has not yet been proposed. One major reason has been the simplification of dynamic conditions of the charge inside the mill (Morrell, 1993). Laboratory studies have shown that the assumption of a fixed shape for the charge is far from the reality (Liddell, 1986). There have been many attempts to quantify analytically the effect of various parameters on the dynamics of mill charge (McIvor, 1983; Vermeulen and Howat, 1986; Powell, 1991; Morrell, 1993; Augustine and Moys, 2006; Cleary, 2009; Hosseini et al., 2011).

1.1. Charge motion: a background

It appears that White (1905) was the first person who tried to study the charge motion analytically. Later Davis (1919) related the charge motion to power draw. Their works on determining the charge trajectory were similar; they assumed the material inside the mill as a locked charge which moves in a circular path until it reaches the point of equilibrium. Grinding elements start their free flight after the point of equilibrium in a parabolic track until they hit the mill shell. In this type of studies parameters such as liner profile, friction forces, charge and interaction of grinding elements were ignored.

Powell (1991) analysed the charge motion in detail and developed a theoretical model, which was based on the fundamental laws of motion, to describe the motion of an isolated rod or ball in a rotary mill. He applied dynamics principles to determine the effect of liner profile on charge motion. Nevertheless he only considered the outermost layer of charge (single ball) and ignored the interactions of grinding elements.

According to his approach if the grinding media is positioned at the tip of lifter it will start its free flight after the point of equilibrium. Otherwise, it will start to role or to slide on the lifter surface until it reaches the edge of the lifter. Then it will fall into free flight (Powell, 1991). When the grinding media reaches the edge of liner, the reference frame should change to a Cartesian coordination with its origin positioned at the mill centre to simplify the calculations.

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The speed of the particle composed of its linear velocity parallel to the lifter face and angular speed resulted from mill rotation. These two types of speeds should resolve into components parallel with Cartesian axes to calculate the charge trajectory. The free flight of charge will end when it encounter the mill shell (Yahyaei and Banisi, 2010).

Morrell (1993) studied the effect of liner profile, mill speed and mill total filling on the shape of load. He used a laboratory mill with one transparent end and photographed the load under various operating conditions. In Fig. 1, description of Morrell from the charge inside the mill is presented.

The variation of the toe and shoulder positions for three different liner profiles at various mill speeds and fillings were studied in his work. Then he proposed the following empirical equations to relate the positions of toe and shoulder and inner load radius to mill speed and filling (Morrell, 1993). In his work the load trajectory was not studied.

$$\theta_T = 2.5307(1.2796 - J_t)\left(1 - e^{-19.42(\varphi_c - \varphi)}\right) + \frac{\pi}{2} \tag{1.1}$$

where θ_T is toe angle (radians), φ is the fraction of theoretical critical speed at which the mill is run, φ_c is the experimentally determined fraction of the theoretical critical speed at which centrifuging was fully established.

$$\varphi_c = \varphi; \quad \varphi > 0.35(3.364 - J_t) \tag{1.2a}$$

$$\varphi_c = 0.35(3.364 - J_t); \quad \varphi \leqslant 0.35(3.364 - J_t) \tag{1.2b}$$

J_t is fractional mill filling.

To ensure that at centrifuging speed the angular displacement of the toe and shoulder converged to the same value ($\frac{\pi}{2}$ radians), the shoulder angle (θ_s) was chosen to be expressed as a function of θ_T. The following equation form was used:

$$\theta_s = \frac{\pi}{2} - ((0.3386 + 0.1041\varphi) + (1.54 - 2.5673\varphi)J_t)\left(\theta_T - \frac{\pi}{2}\right) \tag{1.3}$$

Then radial distance from the axis of rotation (r_i) can be found from:

$$r_i = r_m\left(1 - \frac{2\pi\beta J_t}{2\pi + \theta_s - \theta_T}\right)^{0.5} \tag{1.4}$$

where r_i is the charge inner radius (m) and r_m is mill radius (m).

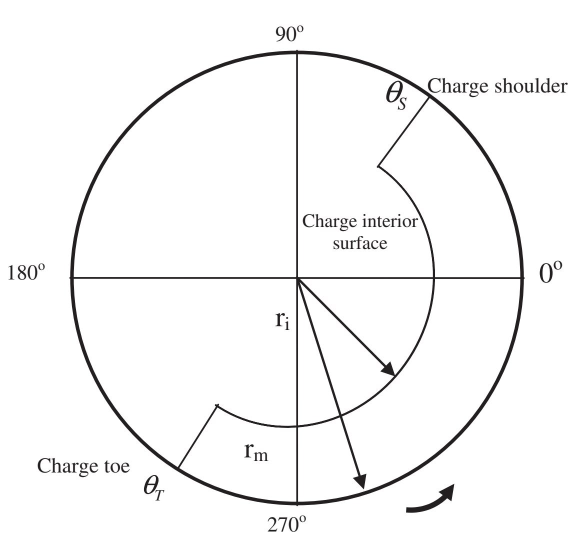

Fig. 1. Simplified charge shape inside the mill (Morrell, 1993).

β is the fraction of the charge bounded by the toe, shoulder and charge inner surface (Morrell, 1993).

Mishra and Rajamani (1990) pioneered the application of 2-D discrete element method (2-D DEM) to grinding mills and demonstrated capabilities of numerical modeling. After considerable increase in computational power of computers, 3-D DEM utilized which was closer to reality since it took the mill lengthwise interactions into account. Thereafter, 3-D mathematical modeling (3-D DEM) was the common approach in most of works, particularly in modeling AG and SAG mills due to complexity of these machines (Cleary et al., 2001; Rajamani et al., 2002; Cleary et al., 2003; Djordjevic et al., 2004; Rajamani et al., 2006; Powell et al., 2008; McElroy et al., 2009).

Hosseini et al. (2011) focused on measuring the internal mill parameters through the use of vibration/acoustic signal obtained from the mill. This methodology was developed to simulate on-the-shell acoustic signal emitted from tumbling mills using the information extracted from a DEM simulator. Some other researcher carried out similar works (Pax, 2001; Behera et al., 2007; Huang et al., 2009; McElroy et al., 2009).

Kiangi and Moys (2006) measured the load behaviour in a dry pilot mill as a function of mill speed and load filling using an inductive proximity probe. They detected the shoulder and toe positions and direct impacts onto the mill shell by the cataracting balls. Comparisons between the inductive proximity probe and the force probe revealed that inductive probe was more superior in measuring the shoulder position. Kallon et al. (2011) developed and tested a model linking the circulation rate of charge particles with physical mill parameters (load fraction, shoulder angle and friction) using experimental data derived from positron emission particle tracking (PEPT). Their experimental results showed clear cascading motion at 60%, cataracting at 75% and partial centrifuging at 90% of the critical speed.

Pérez-Alonso and Delgadillo (2012) presented an experimental validation of a 2-D DEM code by digital image analysis of the velocity profiles of the balls, the toe and shoulder angles and the predicted power draw. They compared experimental values with the simulated data using different charge lifters and charge levels and finally concluded that such DEM predictions represent an accurate description of the process in a tumbling mill.

There have been other works regarding the factors influencing the charge trajectory (Moys, 1993; Cilliers et al., 1994; Valderrama et al., 1995; Morrell and Kojovic, 1996; Van Nierop et al., 2001; Kalala et al., 2008; Cleary, 2009; Si et al., 2009).

In order to determine the charge trajectory Yahyaei and Banisi (2010) developed a software called GMT (Grinding Media Trajectory) which was based on Microsoft Excel© spreadsheet using the method proposed by Powell (1991). In this software Morrell's (1993) approach was applied to determine the charge shape in which he calculated positions of the toe and shoulder and inner charge radius based on mill speed and filling.

The GMT software only considers the outermost layer of charge (single ball) and ignores the interactions of grinding elements. Also, the liner characteristics such as lifter face angle, number of lifters and lifter height were not taken into account. Therefore, in this research the measured charge trajectory and shape in the model mill was compared with the GMT results. The tumbling ball charge was photographed with a high-speed camera. Measurements from the photographs were made of the angular displacement of the toe, toe departure, shoulder and charge impact point. The idea was to propose empirical relationships to correct the charge shape and trajectory obtained for a single ball. These relationships were validated in the model mill by using the new liner of Gol-E-Gohar iron ore complex AG mill.

As part of this study, to improve comminution efficiency in the Gol-E-Gohar iron ore complex AG mill the lifter face angle