Minerals Engineering 105 (2017) 22–35

Contents lists available at ScienceDirect

Minerals Engineering

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

Effect of lifters and mill speed on particle behaviour, torque, and power consumption of a tumbling ball mill: Experimental study and DEM simulation

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ARTICLE INFO

Article history:
Received 2 April 2016
Revised 26 October 2016
Accepted 29 December 2016

Keywords:
Experimental study
DEM simulation
Particle behaviour
Ball mill

ABSTRACT

Crushing and grinding consume most of the energy in mineral processing. Ball mill is an important kind of grinding equipment used to decrease the size of ore particles. The power consumption of a ball mill is one of the most important parameters to consider in the design of a ball mill because it determines its economic efficiency. The power consumption is usually determined by charge fill level, lifter height, lifter number, and mill speed. However, almost all of the classical theories for calculating the power consumption of ball mills disregard the effect of lifters and only focus on rotation rate, charge fill level, as well as size and shape of grinding media, thereby may causing errors. Discrete element method (DEM) can simulate the motion and interaction of particle materials. Thus, this method is widely used to simulate the working process of ball mills, which yields many valuable research outcomes. Moreover, the results obtained from DEM usually should be validated with experiments. In this paper, simulation results of particle behaviour, mill torque, and power consumption obtained from DEM simulation are compared with experimental results in detail to validate the correctness of the simulation results. Especially, the particle behaviour is validated both qualitatively and quantitatively. The DEM results are shown to be highly consistent with the experimental results. The torque of liners and baffles are affected by lifter height, lifter number, and mill speed. Moreover, the changes in the torque and power consumption of a ball mill can be effectively explained using two important factors: lifter and particle area ratio.

1. Introduction

Mill liners protect mill shells from abrasion and lift ore particles and grinding media to a high position. Therefore, liners/lifters must be able to bear high-impact loads during the grinding process. The wear rate of these components is high, and these parts tend to break or incur wear-out failure, which can seriously affect the production efficiency of ball mills. Thus, the research on liner structure and configuration of ball mills is crucial to improve the production ability and economy of ball mills. The DEM is a powerful tool to effectively explain the movement of ore particles and improve the operation, production, and efficiency of ball mills by optimizing their structure. Many researchers have used DEM to extensively study ball mills, and they have obtained valuable results in the last two decades (Rajamani and Mishra, 1996; Morrison and Cleary, 2004; Djordjevic, 2005; Powell and McBride, 2006; Powell et al., 2006; Cleary et al., 2008; Morrison and Cleary, 2008; Cleary, 2009a; Mulenga and Moys, 2014; Cleary, 2015; Geng et al., 2015; Bbosa et al., 2016).

The structural characteristics of liners/lifters and mill speed substantially influence particle motion in ball mills and dramatically influence the grinding process and power draw of ball mills. DEM was first used by Mishra and Rajamani (1992, 1994a,b) to study the motion of ball charge and the power draw of tumbling mills in two dimensions; in the study, the effect of liners was also considered. Cleary (1998) then studied in great detail the effect of mill speed on charge behaviour, torque, and power draw; although they obtained instructive results, such results were still based on two dimensions. Cleary (2001a,b) then made significant progress by using three-dimensional models to predict the power draw of semi-autogenous (SAG) mills. Generally, fill level, mill speed, shape and number of lifters, and particle properties (friction coefficient as well as shape and size of particles) substantially influence the particle behaviour and power draw of ball mills (Cleary, 2001c; Hong and Kim, 2002; Djordjevic, 2003). Cleary et al. (2003) then

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http://dx.doi.org/10.1016/j.mineng.2016.12.014
0892-6875/

provided an innovative approach to investigating ball mills by evaluating the accuracy of the results obtained from 2D and 3D DEM simulations on the basis of a comparison of the simulation and experimental results; the researchers also quantitatively studied how particle shape affects the power draw of ball mills. Hlungwani et al. (2003) adopted the DEM simulator Millsoft (2D) to study the effect of lifter shape and mill speed on power draw and load on the lifters as well as to verify the results obtained with experiments. Powell and McBride (2004) illustrated media motion and grinding regions (head, departure shoulder, center of circulation, equilibrium surface, bulk toe, and impact toe). The wear rate and service life of liners/lifters can significantly affect the behaviour of ball mills, whereas the load applied on lifters determines the lifespan of lifters (Kalala et al., 2005, 2008). Makokha and Moys (2006, 2007) and Makokha et al., (2007) analyzed the changes in grinding efficiency and productivity when cone lifters are used. Furthermore, a comminution model was built by Powell et al. (2007, 2008) to tackle the fundamental causes of rock breakage in various comminution devices. Cleary (2009b) made major progress by studying a two-chamber cement mill in full scale. Generally, these researchers have performed a significant amount of work and obtained interesting and important results. Nevertheless, progress can still be made, including in the qualitative validation of particle behaviour or charge motion.

Major progress has also been achieved in the study of particle motion in ball mills and validation of the results obtained from DEM (Powell and Nurick, 1996; Govender et al., 2001; Govender and Powell, 2004; McBride et al., 2004). Recently, Rezaeizadeh et al. (2010) conducted a series of experiments and concluded that increasing mill speed and lifter number as well as reducing fill level can raise the impact load and frequency of particles, which can in turn improve the efficiency of ball mills. Powell et al. (2011) used EDEM software to predict the wear rate of lifters and built a model to study the relationship between liner shape and the efficiency of ball mills. Wang et al. (2012) then examined the distribution of collision energy and maximum impact energy and analyzed how the size of steel particles affects grinding efficiency. Maleki-Moghaddam et al. (2013) simulated the flow of particles inside a ball mill using GMT software, verified the results through experiments, revised the particle trajectory equation, and optimized the design of liners. Toor et al. (2013) optimized the design of liners to prolong their life, increase mill production, and decrease power consumption. Cleary and Morrison (2016) and Weerasekara et al. (2016) used DEM to study the comminution mechanisms and energy utilization of ball mills. The use of DEM coupled with other numerical methods to study ball mills has become a hot research topic (Jonsén et al., 2011, 2012; Beinert et al., 2015; Mayank et al., 2015).

None of the empirical formulas for computing the power consumption of ball mills considers the effect of lifters (Bond, 1961; Chen Bingchen, 1981). In the present study, the effect of lifter height, lifter number, and mill speed on the particle behaviour, torque, and power consumption of ball mills, respectively, are analyzed quantitatively by DEM and experiments. Specifically, particle behaviour is validated both qualitatively and quantitatively in detail. The results of this study are expected to provide insights into the motion of particles and may help optimize the working process of ball mills on the basis of lifter height, lifter number, and mill speed. The changes in the torque and power consumption of ball mills can be effectively explained using two important parameters: lifters and particle area ratio. The torque of liners and baffles is also examined when the operating parameters of ball mills are changed. The results indicate that lifter height, lifter number, and mill speed affect the magnitude of torque on liners and baffles.

2. Methodology

2.1. Empirical formulas

Many formulas can be used to calculate the net power of a mill. These formulas come in two basic types: those used when a ball mill works at a relatively low speed and those used when a ball mill works at a relatively high speed. The dividing line is shown in Fig. 1 (Hou, 2015).

When a ball mill works at a relatively low speed, its net power can be obtained from Formula (1) as follows:

$$N_e = mgrn \times \frac{\sin^3(\Theta/2)\sin\beta}{45\varphi}, \tag{1}$$

where m is the mass of the charge. A schematic of the parameters in Formula (1) is shown in Fig. 2 (Hou, 2015). Fig. 2 shows the horizontal section of a ball mill, O is the center of the mill section, and OY is the vertical axis. According to Fig. 2, r_u is the distance between O and the centroid of the charge (M), r is the internal radius of the mill, Θ is the angle of charge (°), and n is the rotational speed (rpm).

When a ball mill works at a relatively high speed, its net power consumption can be determined, as indicated in Table 1, where m is the mass of the charge, φ is the fill level, ψ is the rotation rate (constant fraction of the critical speed), ρ is the density of the granular pile, V is the internal volume of the ball mill, D is the internal diameter of the ball mill, and d_j is the maximum diameter of the steel balls.

2.2. DEM

DEM is a numerical method to deal with the kinematic and mechanical behaviour of complex granular systems. DEM regards the discrete system as many discrete units with certain shapes and masses. DEM is mainly used in kinematics and mechanics research on discrete particles, such as rocks, soils, and powders, to conduct a complex dynamic calculation of granules under complex physical conditions. DEM has been widelyused in mining, chemical engineering, and biological medicine, particularly in the research on ball mills. DEM is a highly convenient approach to determine the particle behaviour, torque, and power draw of ball mills in different conditions. Consequently, DEM is used in the present study as a tool to examine the effect of lifters and mill speed on the particle behaviour, torque, and power draw of a ball mill. The material and numerical parameters used in the DEM model are shown in Table 2. The DEM code used in this study is EDEM.

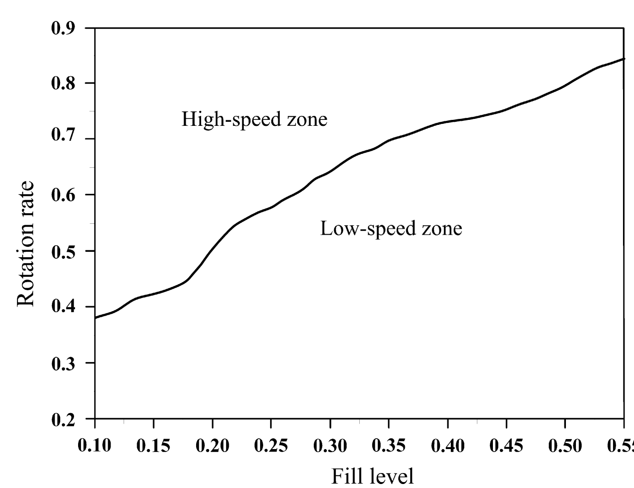

Fig. 1. The dividing line of formulas.