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A generic wear prediction procedure based on the discrete element method for ball mill liners in the cement industry

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ABSTRACT

A generic procedure to predict the wear evolution of lining surfaces, namely the spatial distribution of wear and the progressive modification of the geometry due to wear, is introduced in the context of shell liners in ball mills. The wear data is accumulated on the surface of the liner by 3D discrete element method (DEM) simulations of the ball charge in an axial slice of the mill, which is either closed by a periodic boundary condition or by frictionless end walls. The calibration of this wear data with the measured wear profiles of the shell liner in a 5.8 m diameter industrial cement tube mill shows that the tangential damping energy defined by the linear spring-slider-damper DEM contact law is the best fitting wear model of 6 different models. The gradual update of the liner shape delivers adequate results for liners without an axial height variation, while the accuracy of fully variable geometrical modifications is limited by the computation time. Nevertheless, detailed phenomena, like the creation of grooves in the liner, were for the first time numerically modeled.

1. Introduction

Ball mills, i.e. rotating cylindrical drums filled with a feed material and several hundred thousand metal balls, also known as the charge, are a major category of grinding devices in mineral processing and cement production (Fig. 1). Grinding is the final stage of particle size reduction, also known as comminution, which consists in breaking already small ore or clinker particles into much smaller ones (several mm to several μm). In ball mills, the particle breakage results from collisions between balls in the presence of the feed material, which got trapped in between them as explained by Wills and Napier-Munn (2005).

Typical ball diameters range from 10 to 150 mm, thus weighting 1 g to 4 kg. Moreover, ball mills have on average a 4 m diameter and a 5–10 MW power consumption. As a result of the energetic motion of the balls, the environment inside of the mill is highly aggressive in terms of wear. For this reason, the mill shell, which is the cylindrical drum of the mill, and the lateral end walls are protected by wear-resistant, replaceable metal plates called shell and head liners. Besides their protective function, liners are also responsible for the energy transfer from the mill to the charge. In the case of the shell liner, the efficiency of the energy transfer is characterized by its lifting ability. This is the ability of the liner to move the charge to a higher position in the mill due to its particular shape so that this charge can cascade more powerfully without, however, cataracting onto the liner, which would lead to its accelerated wear. The lifting ability usually decreases over time since the wear increasingly smoothes the liner. Hence, liner manufacturers try to design shape preserving shell liners with minimal wear rates, which keep the energy transfer maximum over time and enhance their lifespan. This design optimization is important since ball milling is very energy intensive and therefore costly. For instance, around 110 kWh of electrical energy are required to produce one ton of cement; 70% of this energy is used to grind the raw material and the clinker according to Kawatra (2006). Moreover, at production outputs of around 300 tons/hour, it is easily understandable that the downtime due to the liner replacement has to be reduced as much as possible. Therefore, predictions of the liner wear can become a significant competitive advantage.

The classical design strategy of the shell liner profile is experimental testing. Because of the harsh environment inside of the mill and the relatively long lifespan of shell liners in ball mills reaching several years, this strategy is difficult and slow. As a result of the recent advances in performance of computer hardware, computational engineering becomes a more popular alternative way to solve this problem. In general, liner wear simulations are based on three elements: a charge motion model, a material wear model and a geometrical update of the liner. The charge motion model is

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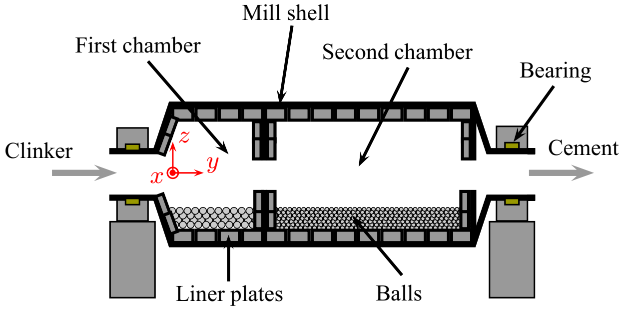

Fig. 1. Description of a ball mill in the cement industry.

used to simulate the motion of the balls in order to calculate the input data of the wear model, like the impact energy or the sliding distance, for specific regions of the liner. In the context of liner wear, the motion of the charge was first numerically predicted by simplified ball charge models as described in Arekar (2004), Radziszewski (1997), Radziszewski and Morrell (1998), Radziszewski and Tarasiewicz (1993a), Radziszewski and Tarasiewicz (1993b), then by 2D discrete element method simulations (DEM, Section 3) as in Cleary (1998), Glover and De Beer (1997), Kalala and Moys (2004), Kalala et al. (2005a), Kalala et al. (2005b), Kalala (2008), Kalala et al. (2008) and finally by 3D DEM simulations, see Cleary (2001b), Cleary et al. (2009), Franke et al. (2015), McBride and Powell (2006), Powell et al. (2011) and Qiu et al. (2001). The 3D discrete element method is currently the most accurate simulation method of the charge motion in ball mills. Nevertheless, it is limited by the significant computation time of full-scale industrial applications as illustrated by Cleary (2009). The wear-related output data of the charge motion model is then transformed into a material volume loss by a wear model, which is the key to accurate wear predictions. A large variety of wear models has been used in the literature about ball mill liner wear:

- the Archard wear equation defined by Archard (1953, 1980) and used by McBride and Powell (2006), Glover and De Beer (1997), Qiu et al. (2001), Radziszewski and Tarasiewicz (1993a), Radziszewski and Tarasiewicz (1993b);
- the formally similar abrasion wear equation defined by Rabinowicz (1995) and used in Radziszewski and Tarasiewicz (1993a), Radziszewski and Tarasiewicz (1993b), Radziszewski (1997) as well as indirectly in Rezaeizadeh's pressure model (see Rezaeizadeh et al., 2010) or Powell's wear model with diameter (see Powell et al., 2011);
- Finnie's erosion law defined by Finnie (1972, 1992) and applied by Cleary (1998);
- Kalala's two component abrasion/adhesion and impact wear model defined by Kalala (2008) based on Sheldon-Kanhere's and Wellinger-Breckel's impact wear models, see Sheldon and Kanhere (1972), Wellinger and Breckel (1969);
- Cleary's four component wear model defined by Cleary (2001b, 2009) with the very promising shear energy component also used by Franke et al. (2015)

This diversity shows that no consensus on the wear model has yet been reached. Notice also, that the previous wear models can be classified into two categories according to the wear mechanism: either tangential abrasion or normal impact wear. Wear by corrosion has therefore not been directly modeled and it will also not be considered in this paper, which focuses on dry ball milling. Finally, the geometrical update of the liner is the consequence of the material volume loss determined by the wear model. Since the liner is usually represented by line segments in 2D and triangular facets in 3D simulations, its geometry is updated by displacing their vertices based on the material loss calculated for each segment or facet. How exactly these vertices are displaced is either not explicitly described in the literature, e.g. Cleary et al. (2009), or very restrictive, e.g. Kalala (2008). Moreover, spatial smoothing and a large number of adjusted coefficients affect the credibility of former models, see Kalala (2008). Detailed reviews about liner wear simulations can be found in Arekar (2004), Kalala (2008) and more recently in Boemer (2015).

In this paper, each of the three issues mentioned previously, namely, the computational limitations of the charge motion model, the large variety of material wear models and the restrictive geometrical update of the liner, will be addressed. First, a specific charge motion model based on the 3D discrete element method will be studied to define a reasonable trade-off between the size of the full-scale mill and the computation time. Hence, only an axial slice of the mill is simulated with two different boundary conditions applied at its lateral end walls. More precisely, the periodic boundary condition in DEM simulations, see Cleary (2001b), which allows balls leaving an axial slice of the mill from one side to re-enter the slice from the other side, is compared with an axial slice of the mill closed by walls, which only have a normal interaction with the balls, i.e. that no tangential interaction or friction is simulated between the walls of the slice and the balls. This boundary condition renders it possible to take into account the axial motion restriction of the balls due to the lateral end walls in the full-scale mill at a certain distance from these walls, where no direct friction against them exists anymore. The resulting structural arrangement of the balls and the particular wear distribution have never been mentioned before in the literature to the best of the authors' knowledge. Second, the wear profile evolution of a shell liner plate will be simulated by the 6 most promising wear models found in the literature. In order to determine, which of these models fits best with the reality, the results will be validated by experimental wear profiles. These wear profiles were measured on a shell liner plate in the first chamber of a 5.8 m diameter cement grinding ball mill monitored during a decade by the company *Magotteaux International s.a.* The resulting optimal wear model will only depend on one single parameter. Hence, the influence of adjusted parameters on the results is reduced. Third, a general procedure to update the geometry of the liner due to the material loss is introduced. In particular, the necessity of spatial smoothing to obtain realistic wear surfaces is studied. Solving the previous three main challenges finally leads to a generic method able to predict the liner wear and to the tentative conclusion that a liner design with grooves similar to the real grooves, which are created over time by wear, might increase the lifespan of the liner.

This paper is structured in three sections: first, the experimental data and the corresponding setup are described. Based on this setup, a charge motion simulation, which is necessary to sample the load leading to wear, is then defined. The charge motion simulation is finally used in combination with the wear model and the updating strategy of the geometry to predict the wear evolution of the liner plate by a wear simulation. The results are generally explained in the same section than the method, which was used to calculate them, in order to simplify the explanation.

2. Experimental data

In this paper, the wear evolution of a liner plate in the first chamber of an industrial 5.8 m diameter cement ball mill, also known as a tube mill, with two chambers is studied on the basis of the experimental data provided by the company *Magotteaux International s.a.* The total length of the mill is equal to 17.14 m, while the first chamber is only 5.1 m long. The mill rotates at