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Development of models relating charge shape and power draw to SAG mill operating parameters and their use in devising mill operating strategies to account for liner wear

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ABSTRACT

A set of 22 three-dimensional DEM simulations are used to understand and quantify the relationship between key charge locations and three important operating parameters – fill level, lifter height and mill speed for a generic SAG mill. The charge shape and location are characterised by the shoulder, head, bulk and impact toe positions and are assessed by analysis of particle trajectories and the spatial variation of the pressure on the liner. Parametric models, created as a best fit to the DEM mill data, are used to relate these charge shape characteristics and the power draw to these operating parameters. They also allow inverse prediction of the fill level and lifter height (or wear state) from measurements of the charge structure and the mill speed. Such models can then be used to interpret experimental measurement data for SAG mills and to infer charge structure. The paper will also explore how such parametric models can be used to create operational management strategies (in terms of how to vary control variables such as target mill fill level and mill speed) in order to maintain chosen performance attributes over the wear life cycle of the liner. Examples of development of strategies that preserve for example, the bulk toe or the power draw of the mill are demonstrated.

1. Introduction

SAG (semi-autogenous grinding mills) are large cylindrical chambers with conical ends, that are partially filled with rock and steel grinding media, and which rotate about their central axis at typically 75–82% of the critical speed required to centrifuge the charge. They can have diameters up to 44 ft or 12.9 m and are used for primary grinding, mainly in mineral processing, using a coarse feed (up to 350 mm diameter rock) coming from the crushing stage of the grinding circuit. The rotation of the mill leads to the charge distribution having a distinctive shape that is often sometimes described as kidney shaped. In this flow pattern, particles near the mill liner move upwards with the mill liner rotation, reaching a high point where the centrifugal and gravitational forces balance (usually termed the "shoulder") and then flow downwards with a free surface that is usually bi-linear in shape with a steep gradient directly down from the shoulder followed by a much shallower gradient out to the start of the charge (usually termed the "toe" or "bulk toe"). If large and/or steep lifters are used in the liner design to lift the charge then some particles are thrown on high ballistic trajectories (termed the cataracting part of the flow) and impact on the liner in a region above the toe. The uppermost limit of this direct liner impact zone is sometimes termed the "impact toe". Grinding is produced by a range of mechanisms including high speed impact, abrasion, chipping and nipping of small particles between large ones (see Cleary and Morrison (2016) for a summary of the mechanisms).

DEM (the Discrete Element Method) has been used successfully for modelling grinding mills for many years now. The first such usage was reported by Mishra and Rajamani (1992, 1994) and has been used by Rajamani and Mishra (1996), Cleary (1998,2001a,2001b,2001c,2004,2009), Cleary et al. (2008), Herbst and Nordell (2001), Morrison and Cleary, (2004, 2008), Djordjevic et al. (2003, 2005, 2006), Jayasundara et al. (2006), Kalala et al. (2005a, 2005b), Powell et al., (2006,2011), Carvalho and Tavares, (2011), Delaney et al. (2013), Tavares and Carvalho (2009) and many authors since then. Conference special issues SAG2006 (Mular et al., 2006), DEM2007 (Cleary and Morrison, 2008) and SAG2011 (Major et al., 2011) provide a recent selection of such DEM mill related papers. A good review of the status of DEM in modelling comminution is given by Weerasekara et al., (2013).

DEM is able to predict the shoulder, toe and impact toe locations for specific mills and operating conditions and can be used to relate the measured charge structure back to the liner and operating conditions.

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Such predictive regression models were developed by Owen and Cleary (2015) for an 8.4 m generic SAG mill. This study included two parameters; fill level and lifter height which were varied systematically to understand the resulting variation of charge structure and liner pressure. These models can be used to estimate the volumetric fill level and lifter wear as functions of the measured charge shape parameters, namely the head, shoulder, bulk toe and impact toe (as measured in Campbell et al. 2001). These regression models were created as best fits to predictions from a series of 3D Discrete Element Modelling (DEM) simulations carried out for the generic SAG mill using various lifter geometries and fill levels.

In this paper, we extend the analysis by including the mill speed as a third operating parameter. Mill speed is a critical operating parameter and varies between mills and can often be varied over time when the mill has a variable speed drive in order to either compensate for liner wear or to achieve other operational goals. Using a Design of Experiment (DOE) method a comprehensive series of 22 simulation conditions is defined. Three-dimensional DEM simulations are then performed for a generic 8.4 m diameter SAG mill for different combinations of lifter geometry (that emulate liner wear states), fill level and mill speed. The characteristic charge structure locations (head, shoulder, bulk toe and impact toe) are measured for each set of conditions and best fit models then developed. This provides a fast method for estimating the mill liner wear state and charge fill level from measured key charge locations and the mill speed. These can then be used to determine the mill condition liner condition and current fill level from measurements of the charge location. Inverse models that allow the key charge shape characteristics and also the net mill power draw to be calculated from the operating conditions are also developed. The relationships of the mill charge characteristics, the mill operating parameters and the DEM derived database of simulation predictions for the SAG mill are shown schematically in Fig. 1. The backward direction fitted models then allow definition and evaluation of mill control strategies that provide a quantitative basis for modifying the mill operating conditions (namely mill fill level and mill speed) in response to liner wear and the evolving liner geometry shape over its life cycle. This information can be used as part of a control strategy for the mill and to assist with re-line scheduling.

2. DEM method

A soft particle implementation of DEM is used in this work. This allows each collision between combinations of particles and between particles and their environment such as the liner of a mill to be modelled. The particle equations of motion are then solved for each particle in the mill. The method is described in more detail in Cleary (1998, 2004, 2009) and the code described there is used in this work.

In a soft particle method, the particles are allowed to overlap and the amount of overlap Δx, and normal v_n and tangential v_t relative velocities determine the collisional forces via a contact force law. A linear spring-dashpot model is used for particle-particle and particle-boundary collisional force. The normal force is given by:

$$F_n = -k_n \Delta x + C_n v_n \tag{1}$$

F_n consists of a linear spring to provide the repulsive force and a dashpot to dissipate a specified proportion of the relative kinetic energy. The maximum overlap between particles is determined by the stiffness k_n of the spring in the normal direction. The normal damping coefficient C_n is chosen to give the required coefficient of restitution ε (defined as the ratio of the post-collisional to pre-collisional normal component of the relative velocity), and is given in Thornton et al. (2013). The tangential force is given by:

$$F_t = \min\{\mu F_n, \sum k_t v_t \Delta t + C_t v_t\}, \tag{2}$$

where the vector force F_t and velocity v_t are defined in the plane tangent to the surface at the contact point. The integral term represents an incremental spring that stores energy from the relative tangential motion and models the elastic tangential deformation of the contacting surfaces, while the dashpot dissipates energy from the tangential motion and models the tangential plastic deformation of the contact. The total tangential force F_t is limited by the Coulomb frictional limit μF_n, at which point the surface contact shears and the particles begin to slide over each other. Other contact models could be used for such modelling. Details of alternative models and comparisons of their predictions for single particle oblique collisions with walls are given for all such inelastic contact models in Thornton et al., (2013).

3. Generic SAG mill geometry and operating conditions

SAG mills can have diameters up to 12.9 m. A three-dimensional slice of a generic intermediate size 8.4 m diameter SAG mill is used here. This study was performed using a series of DEM simulations whose details are given in Table 1. Different combinations of fill level, lifter height and mill speed were simulated. The liner profiles used in this study are shown in Fig. 2 (with all the lifters being the same as each other) and are the same ones used in an earlier simpler two parameter study (Owen and Cleary, 2015). The different lifter heights can occur as a result of either selection of different size new lifters in the mill or as the result of liner wear. The largest lifter had a height of 300 mm and a face angle of 15 deg; while the shallowest lifter had a height of 50 mm and a face angle of 25 deg The lifter profiles with intermediate heights and face angles are shown in Fig. 2. Other combinations of lifter height

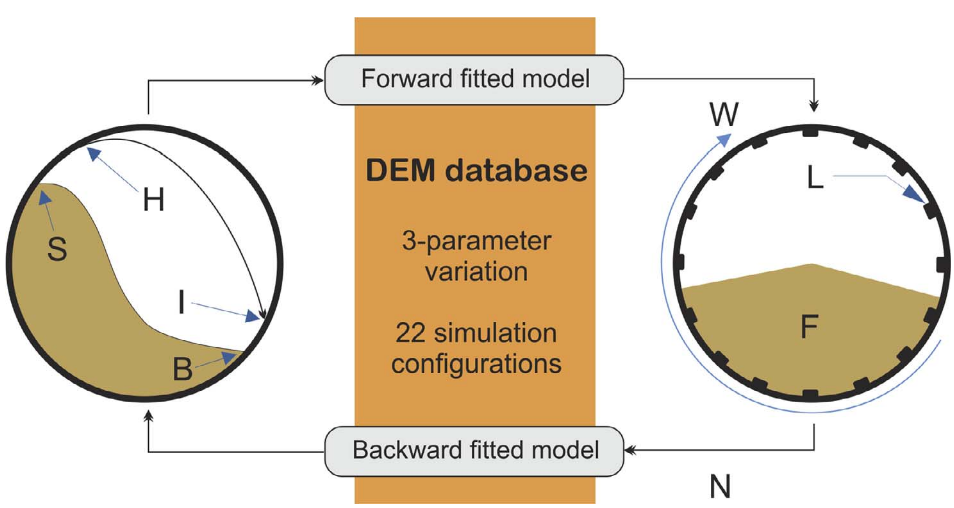

Fig. 1. Schematic showing the relationship between the charge shape characteristics (left) and the mill operating parameters (right) and the connection through the DEM database of simulation cases of the forward and backward fitted predictive models.