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Understanding performance variation of a HICOM® mill with operating conditions and media attributes

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ABSTRACT

Grinding mill performance is typically controlled by making operating adjustments and taking external measurements to infer what is happening inside the mill. So optimising existing machines or designing new ones is difficult and expensive. DEM now offers a broad range of capabilities to look inside these mills to gain improved understanding of charge dynamics, prediction of the power draw and knowledge of the energy utilisation. In this paper, we demonstrate these capabilities of DEM for machine design by exploring the performance variations in a HICOM mill with changing operating conditions (such as fill level and mill speed) and different material properties (such as particle size, density and friction). These predictions compare well with existing experimental observations and provide new insights into the flow dynamics inside the HICOM mill. Together they demonstrate how the DEM method can be used in a mill optimisation or design process.

1. Introduction

Grinding mills are complex machines used for the reduction of particle size due breakage induced during flow of particulates within the machine. Process performance is typically controlled by many operating parameters (such as fill level, media size, shape and density, feed material size, shape and density, and mill speed) and by mill liner design. Optimisation of existing machines is a difficult and expensive process due to the difficulty in measuring anything within the grinding chamber and due to the variability in feed and operating conditions. Design of new machines and scale-up of existing machines is even more difficult since there is not process information available until at least one working prototype is constructed — which makes the process slow, expensive and involves not inconsiderable commercial risks.

In grinding devices, it is typically neither possible to see the particles nor to observe the breakage because the mill shell is solid and feed and discharge openings are obscured and the mill environment is either dusty or muddy (depending on whether it is operated dry or wet). Furthermore, almost all instruments placed in the mill are easily damaged and destroyed by the hostile grinding environment. Non-intrusive tomographic measurement approaches can be used to provide some information but are typically restricted to lab scale (see Lameck et al., 2006; Kiangi et al., 2013; Katubilwa and Moys, 2011; Ghorbani et al., 2011; Govender et al., 2004, 2013). Similarly visualisation through partially transparent mills is possible only for lab scale and minimally abrasive conditions (Cleary and Hoyer, 2000; Venugopal and Rajamani, 2001; Cleary et al., 2003; Maleki-Moghaddam et al., 2013; Mulenga and Moys, 2014) and allows only qualitative information to be obtained. For full size mills there are even fewer options for obtaining process information from within the mill. Information on the location of the toe and shoulder positions of charge in wet tumbling mills can be obtained from piezo-electric or conduction sensors in liner bolts that operate by detecting changes in local conductivity when slurry is present (van Nierop and Moys, 1997, 1998; Keshav et al., 2011). Efforts have also been made to measure charge location and structure using acoustic signals (acquired by microphone) from the mill (Zeng and Forssberg, 1993; Pax, 2001; Pax et al., 2003; Si et al., 2009) or vibration monitors (using strain gauges in liner bolts) (see Campbell et al., 2003; Das et al., 2011; Tang et al., 2012; Davey et al., 2012). But these at best provide only an indication of some aspects of the charge shape rather than detailed actionable information on breakage and transport.

The dominant approach has been to use measureable input and output information from the mills. These include feed and product size distributions, feed rates, particle breakage properties, slurry properties and power draw. Typically these are used in calibrated models, typically based on the population balance approach. Early examples include Kelsall et al. (1969), Whiten (1972), Austin et al. (1984), Herbst and Fuerstenau (1980), Rajamani and Herbst (1991), Morrell et al. (1993), Guillaneau et al. (1995), Weller et al. (1996), King (2001), and Loveday and Whiten (2002) which led to commercial software products based on these methods, such as JKSimMet (Morrison and Richardson, 2002). Significant progress in design and optimisation has been made using such empirically based process models over the last 30 years.

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However, they have some key drawbacks which limit full range of mill development and optimisation processes that are needed. These include:

- the model is an averaged fit over many data sets with a broad range of variability in conditions and ores which restricts the accuracy;
- there are many approximations in the process model simplifying the breakage processes and the transport
- it cannot validly be used in conditions that are beyond the operating ranges of the data used to calibrate the model
- it cannot be used for new machines or ones that are non-trivially scaled up.

Over the last 20 years a new approach called Discrete Element Modelling (DEM) has been emerging based on mathematical models of the particle scale processes. This involves modelling as many of the particles as can be afforded and predicting all their collisions with each other and with the mill and the consequent motion of the particles and energy transfers within the mill. It was first introduced as a tool to predict the motion of media within ball mills by Mishra and Rajamani (1992, 1994). These initial models were two dimensional and included only the media. Rajamani and Mishra (1996) applied two dimensional DEM to SAG mills. Cleary (1998, 2001b,c) then included coarse feed into more detailed two dimensional ball and SAG mill models. Cleary (2001a) used such a DEM model to perform one the earliest parametric process performance investigations linking material properties and operating conditions to mill power draw.

Herbst and Nordell (2001) and then Cleary and Sawley (2002) used a slice model to explore three dimensional effects in the same type of coarse feed tumbling mill. Morrison and Cleary (2004) used DEM to investigate the nature of the collisional energy spectra and the collision histories of individual particles and demonstrated that breakage in tumbling mills could not be dominated by balls and rock thrown onto the toe in the cataracting region. Cleary (2004) and Morrison and Cleary (2004) used DEM at a pilot scale to perform the first full three dimensional DEM analyses of particle flow in SAG mills. Djordjevic (2003, 2005) used similar models to estimate the effect of charge size distribution and liner variations on power draw. The first use of DEM to study stirred mills was by Sinnott et al. (2006) and Cleary et al. (2006). Jayasundara et al. (2006) also studied the flow of grinding media in a simplified Isamill using DEM. Djordjevic et al. (2006) also examined likely comminution behaviour in tumbling mills. The emergence of new breakage characterisation methods combined with full three dimensional DEM modelling, including particle breakage led to the introduction of the “Virtual Comminution Machine” concept by and Morrison and Cleary (2008). This was used by Cleary et al. (2008) to study flow and segregation of rock particles within the charge in a periodic slice model of an Isamill and breakage on a grinding table. Jayasundara et al. (2008, 2009) also extended their DEM Isamill model to multiple discs for studying grinding performance. More recently, DEM has been used to compare the performance of lab scale tower and ball mills configured to produce the same product size (Morrison et al., 2009).

As the DEM models have grown in size and complexity they have become sufficiently capable that they can predict charge motion, power draw, energy utilisation and wear. This has led to increasing adoption of this approach to providing detailed information about what is happening in mills (and to attempt to predict particle breakage and product size distributions (Delaney et al., 2013)). Cleary (2009b) used a very large scale three dimensional DEM to explore media behaviour and ball size segregation in a two chamber cement ball mill. Many authors are now using DEM type approaches for exploring and understanding mill performance, see Kalala et al. (2005a,b), Powell et al. (2006, 2008, 2011), Carvalho and Tavares (2011), Weerasekara et al. (2010, 2011), and conference special issues SAG2006 (Mular et al., 2006), at DEM2007 (Cleary and Morrison, 2008) and SAG2011 (Major et al., 2011). A recent review by Weerasekara et al. (2013) indicates the current state of DEM modelling for comminution.

The HICOM mill is a high intensity fine grinding mill used for fine grinding and special particle liberation. This mill was first modelled using DEM by Hoyer and Boyes (1990). Cleary et al. (2010) presented full three dimensional modelling of media flow in a HICOM mill and demonstrated the development of a suitable wear model able to predict the liner life cycle. More recently, Owen and Cleary (2014) used DEM to understand the discharge behaviour of different port arrangements for a HICOM mill. In this paper, we use broad range of capabilities now offered by DEM for mill process improvement to understand media flow and energy utilisation within a HICOM mill for a broad range of operating conditions. We aim to provide usable operational information for the HICOM mill and also to demonstrate how the DEM method can be used in a mill optimisation or design process.

2. Modelling assumptions and mill configuration

The HICOM mill shares some similarities with the centrifugal mill (Hoyer, 1984, 1985). These are able to reach or exceed the energy intensity of stirred mills but take the approach of moving the entire grinding vessel at high speeds in order to produce high accelerations and strong grinding intensities. The grinding chamber of the HICOM mill is a cylindrically symmetric vessel that is smaller in diameter at the top, increasing to around 1/3 from the bottom and then decreasing on approach to the closed bottom. There is a narrow cylindrical neck at the top through which feed material enters. The liner has 8 vertical lifters running from the neck to the base. Ports in the form of circular openings are located between the ribs of the mill liner. These allow fine ground particles and/or optional large liberated ore particles or media to discharge. Typically such a mill will be operated in closed circuit with media being separated from the discharge stream and returned to the mill or fine grates can be placed over the ports to retain media while permitting finer particles to exit. The grinding chamber shape is shown in Fig. 1.

The grinding chamber is inclined at an angle of 4.75° from the vertical, and moves with a nutating motion. The frequencies considered in this study are between 580 and 730 rpm. In performing this motion, the nutation point remains stationary, while points on the chamber below describe circles around the vertical axis having diameters increasing with distance below the nutation point. The nutating mill was filled through the central feed opening with media particles to a specified fill level. This was achieved for this mill by feeding in new material at the top at a rate that matches the discharge rate, so maintaining the charge weight constant. In this study, the discharge ports were blocked off to prevent media charge so that the steady state performance of the mill could be more easily compared. Discharge behaviour for the HICOM mill has previously been studied by Owen and Cleary (2014).

The DEM code used here has been applied extensively to milling applications (see Cleary, 2004, 2009a for details and examples of milling and other applications). The contact model being used is a linear spring-dashpot model. For details of this contact model and comparison to other models for elastic and inelastic collisions see Thornton et al. (2011, 2013).

The DEM method and the DEM implementation used here have been well validated by comparison to laboratory scale experiments. Cleary et al. (2003) compared the charge structure predicted for multiple fill levels and mills speed with experimental photographs for a laboratory scale SAG mill and found very good agreement for three dimensional DEM models. Similar comparison of DEM charge motion and structure predictions were made with high speed photographs for a centrifugal mill (Cleary and Hoyer, 2000) which showed excellent agreement including the ability to predict a change in the dynamic behaviour at low fill levels. More recently, Govender et al. (2013) found extremely good agreement for the charge solid fraction and velocity distributions