Minerals Engineering 86 (2016) 75–95

Contents lists available at ScienceDirect

Minerals Engineering

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

Comminution mechanisms, particle shape evolution and collision energy partitioning in tumbling mills

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ARTICLE INFO

Article history:
Received 30 July 2015
Revised 4 October 2015
Accepted 3 December 2015
Available online 14 December 2015

Keywords:
Tumbling mills
Breakage
Chipping
Rounding
DEM

ABSTRACT

A computational model for use with DEM (Discrete Element Method) is proposed for the five mechanisms applying to particle comminution in AG, SAG and coarse feed ball mills. Chipping and rounding are mechanisms that lead to preferential mass loss from corners and edges of particles and which produce shape change for the particles as well as size reduction. These are controlled by the energy dissipation at a contact and the location of the contact on the surfaces of the particles. These mechanisms lead to rounding or conditioning of angular feed particles. Single impact body breakage is a very weak contributor to overall size reduction with most body breakage occurring via damage accumulation over many contacts. This incremental damage mechanism is inherently less inefficient but leads to size reduction from the many weak collisions experienced by particles within the mill. Finally, size reduction from abrasion is well represented by the shear energy absorption of the particles. Particle size and shape evolution due to chipping, rounding and attrition is demonstrated using a well characterised pilot mill for which detailed particle mass data is available. The relative contributions of the five mechanisms and a quantification of the wasted energy for both AG and SAG charges and for new and substantially comminuted material are reported. Changes in the energy spectra with the decreasing particle sizes over time are described with increases in the fraction of collisions above the elastic energy threshold leading to faster damage accumulation and reduced energy wastage. Finally, it is shown that the attribution of dissipated energy between particles in a collision is material dependent with significantly more energy absorbed by rock particles than balls. This needs to be accounted for in DEM models, particularly when attempting to explicitly predict particle size reduction.

1. Introduction

The Discrete Element Method (DEM) is a computational scheme for predicting the flow of particulates. Since milling is predominately a process involving collisions between particles and between particles and the milling machine, it has been used extensively to investigate different aspects of mill performance. The earliest use for modelling in SAG mills was by Rajamani and Mishra (1996) who used two dimensional DEM to help design lifters by predicting media overthrow. The most common use has been in understanding the charge distribution, material flow patterns, energy utilisation and power draw (Mishra and Rajamani, 1992, 1994; Cleary, 1998, 2001a, 2001b, 2001c; Herbst and Nordell, 2001; Cleary, 2004, 2009; Morrison and Cleary, 2004, 2008; Cleary et al., 2008 and many authors since then including for example the comminution special issue edited by Cleary and Morrison, 2008). A recent review article by Weerasekara et al. (2013) describes the current status of DEM modelling and the challenges related to its use in comminution.

One of the most important aspects of mill performance that has been least studied using DEM is that of particle breakage. Although this is the purpose of milling, the use of DEM for the prediction of size reduction is challenging because several different modes of breakage are active and because the particle change (size and shape) needs to be explicitly included in the DEM model. Commonly DEM simulation is used to provide average process data from which selection functions can be determined for use in traditional population balance models (Tuzcu and Rajamani, 2011; Tavares and de Carvalho, 2009). The accuracy of such models is limited by the ability to adequately characterise the collisional environment and the limited physics captured by the population balance models. To be able to accurately predict, from first principles, breakage, product size distribution and resident particle size

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http://dx.doi.org/10.1016/j.mineng.2015.12.006
0892-6875/

distribution, particle breakage needs to be included directly in the DEM model. The breakage model and the mechanisms that they implement also need to be sufficiently correct to make accurate predictions. This avoids the averaging over the different flow conditions within different parts of the mill that is inherent in approaches that seek to predict particle populations using averaged selection functions. An approach for direct inclusion of breakage in DEM was first proposed by Cleary (2001b). This used a replacement strategy where compressive or impact breakage fracture of a parent particle into finer progeny was represented directly in the DEM model. This model was limited by the use of spherical parent and progeny and the limited ability to include characterised breakage properties. Recently, a more sophisticated variant that can represent breakage of non-round particles into non-round progeny was proposed by Delaney et al. (2010a). This was specifically developed to be able to model incremental breakage due to damage accumulation of particles over many collisions and uses breakage characterisation data from tests such as the JKDWT (JK Drop Weight Test) or JKRBT (JK Rotary Breakage Tester).

At SAG 2006, we reported (Morrison et al., 2006a) the simulated and measured outcomes of treating a well characterised ore in a 1.2 m diameter mill. This well instrumented, pilot scale mill at the University of KwaZulu-Natal had been combined with some new approaches to ore testing to allow different modes of breakage to be tested. It showed that autogenous mill loads of various sizes and shapes could be reasonably predicted by abrasive mass loss proportional to the estimated frictional energy experienced by each particle. However, this approach was inadequate for SAG operation where incremental damage produces more non-trivial body breakage and quite different progeny size distributions. Another drawback of this initial investigation was that the particles were spherical in the DEM models of both the abrasion mill and the pilot mill.

At SAG 2011, we extended this work (Morrison et al., 2011; Delaney et al., 2013) by exploring the accuracy of the breakage prediction when using just an incremental damage mechanism. This used the elastic energy of contacts to estimate the incremental damage that controls the probability of a particle breaking and the progeny produced. Defining E_0 to be the elastic threshold energy at which damage starts to occur, it was found that a range from 3.6 to 5.4 J/kg was needed to produce appropriate amounts of breakage. The model was able to reproduce with good accuracy both AG and SAG product size distributions. In using only the incremental damage, the E_0 values were found to be around an order of magnitude lower that typically measured (Morrison et al., 2007; Whyte, 2005). Much of the size reduction was found to occur from very weak collisions that removed very small mass increments from the particles rather than by substantive body breakage. Essentially, the incremental damage model was also directly predicting attrition of the particles, although little correlation was found between the predicted and measured fine progeny.

In this paper, we identify five key breakage mechanisms and provide details of the computational method for implementing them. We then focus on the surface damage mechanisms by explicitly including the chipping and rounding of non-spherical parent particles in addition to the abrasion mechanism that has been previously reported by Morrison et al. (2006a). This allows us to explicitly predict the size and shape evolution of the particles in the mill resulting from surface damage accumulated over time from their collisions. The surface mass loss rate as a function of energy input is calibrated from one identified rock in the first experiment and this is then used in simulating the evolution of all the particles in three test cases (with differing test conditions). The model predictions using only surface damage form an upper limit on the size of each particle at each time. The nature of the change of shape of the particles during milling is explored in detail as is the variation of these rates with time as the particles become rounder. The decrease in particle size over time will be shown to change the collisional environment in the mill. It will be further shown that as the particles shrink, their specific collision energies increase leading to more collisions being above on the elastic threshold E_0 which will lead to increasing efficiency of the incremental breakage mechanism. Finally, the attribution of collision energy absorption between colliding entities will also be shown to be important and bounds on the splits required to match experiment will be established.

2. Breakage mechanisms in mills

The first few minutes of operation with a fresh charge causes rapid rounding of initially angular particles and a relatively coarse product. The production rate of progeny then decreases to a more or less steady state production rate of much finer progeny. The rate of particle wear can be modelled based on inter-particle friction and shear energy absorption. Under suitable conditions, the number of impacts which exceed the elastic threshold E_0 allows the ore particles to begin to accumulate incremental damage.

Previously (Morrison et al., 2011), postulated five mechanisms occurring in AG, SAG mills and coarser feed ball mills:

- Body breakage (single impact breakage through the particle – the traditionally conceived mechanism occurring in tumbling mills but in reality infrequent in a large SAG mill and completely absent in the pilot mill used here).
- Incremental damage (body breakage due to accumulated damage or fatigue from many weak collisions).
- Attrition or abrasion (mass loss at the surface of rounded rocks as other particles slide over them or they slide over the liner).
- Rounding (preferential and higher abrasive mass loss from sliding at the corners and edges of blocky particles).
- Chipping (loss of corners, edges and larger asperities from small scale body breakage for irregular shaped or non-round particles).

All five mechanisms have been implemented in the DEM code described in Cleary (2004, 2009). For the results reported in this paper, only the last three surface erosion mechanisms are active. The final stage of this work where all the mechanisms are used together to provide a complete representation of the breakage environment experienced by the rock particles will be reported in a following paper. This should, in principle, allow direct prediction of the complete rock size distribution over time.

3. Implementation of size reduction in DEM

3.1. Determination of energy absorbed by a particle from DEM

The contact force is best represented in a collision frame with a normal direction and a tangent plane. This is defined locally at the contact point between the two colliding surfaces. In this frame, using a linear spring–dashpot contact model, the normal force 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:

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

The magnitude of the overlaps Δx between particles is determined by the stiffness k_n of the spring in the normal direction (in N/m). The damping term is proportional to the normal component of the contact velocity v_n. The normal damping coefficient C_n is chosen to give the required coefficient of restitution ε (defined as