



Incremental damage and particle size reduction in a pilot SAG mill: DEM breakage method extension and validation

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ABSTRACT

Applying DEM to prediction of tumbling mill performance is challenging because several different modes of breakage are active in the process. Here we use measured data from a well characterised ore in a well instrumented, 1.2 m diameter pilot scale mill to validate direct DEM prediction of particle size reduction. The key comminution mechanisms involved for a SAG mill are: (1) incremental breakage where parent particles break into progeny based on the cumulative energy absorption above the elastic damage threshold, (2) abrasion, and (3) chipping/rounding due to preferential contact and breakage of corners and edges of non-round particles. In this paper, a method for including incremental damage breakage in DEM is presented. The inclusion of all the size reduction mechanisms in the same DEM framework allows direct prediction of the evolution of the resident rock particle size and shape distributions and the product throughput rate. The surface mass loss mechanisms are shown to be critical for reducing the particle size to the point where the accumulation of incremental damage becomes significant leading to body breakage of these damaged particles. The energy split between ball and rock is also important for exceeding the elastic threshold and creating damage. Comparison of the predicted particle sizes at the completion of ten minutes of grinding operation with the measured experimental values from the pilot mill provides quantitative validation of the breakage predictions of this DEM breakage model.

1. Introduction

At SAG 2006 (SAG, 2006), Morrison et al. (2006) reported the simulated (using the Discrete Element Method–DEM) 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 using an abrasive mass loss for the particles that was proportional to the estimated frictional energy dissipated by each particle. However, this approach was inadequate for SAG operation where incremental damage produces non-trivial body breakage and quite different progeny size distributions. Another drawback of this initial investigation was that the particles in the DEM models of both the abrasion mill (used for calibrating the mass loss rates) and the pilot mill were spherical.

At and after SAG (2011) (SAG, 2011), Morrison et al. (2011) and Delaney et al. (2013) extended this work by exploring the accuracy of the breakage prediction when using just an incremental damage

mechanism. This used the elastic energy of contacts between particles to estimate the incremental damage which then controlled the probability of a particle breaking and the size distribution of the progeny produced. Defining E_0 to be the elastic threshold energy per unit mass of particle at which damage starts to occur (which in these works was assumed to apply to the particles being simulated, it was found that a range from 3.6 to 5.4 J/kg was needed to produce amounts of breakage that were consistent with the experimental results. The model was able to reproduce with good accuracy both AG and SAG product size distributions. However, in using only the incremental damage, the E_0 values were found to be around an order of magnitude lower than typically measured (Morrison, Shi and Whyte, 2007; Whyte, 2005). This discrepancy suggested that a more realistic breakage model was required. Much of the size reduction was identified as occurring 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 behaving as an attrition model for the particles, although little correlation was found between the predicted and measured fine progeny that exited the mill.

More recently, Cleary and Morrison (2016), theorised that five key

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mechanisms were responsible for the size reduction that occur in SAG mills. These were:

1. Body breakage by single impact breakage through the particle—this is traditionally seen as the mechanism occurring in tumbling mills but in reality is infrequent in a large SAG mill and completely absent in the pilot mill used here.
2. Incremental damage where body breakage occurs due to accumulated damage or fatigue from many weak collisions.
3. Attrition or abrasion where mass loss occurs at the surface of rounded rocks as a consequence of other particles sliding over them or their sliding against the liner.
4. Rounding where preferential and higher abrasive mass loss occurs at the corners and edges of blocky particles arising from sliding contact.
5. Chipping where angular or blocky particles preferentially lose corners, edges and larger asperities from small scale volumetric fracture for irregular shaped or non-round particles.

This paper then focused on the surface damage mechanisms by explicitly including the chipping and rounding of non-spherical parent particles in the DEM method in addition to the abrasion mechanism that has been previously reported by Morrison et al. (2006). This allowed direct prediction of the size and shape evolution of the particles within the mill resulting from all the surface damage accumulated over time by each of the particles during their various collisions. The nature of the change of shape of the particles during milling was identified. The decrease in particle sizes over time led to changes in the collisional environment in the mill. Specifically, as the particles shrink, the specific collision energies increase leading to more collisions being above the elastic threshold E_0 which is expected to lead to increasing efficiency of the incremental breakage mechanism. Finally, the attribution of collision energy absorption between colliding entities was shown to be important and a key reason as to why the SAG charge case for the pilot mill behaves quite differently to that of the AG cases despite similar collision energy levels.

In this paper, we propose a new DEM implementation of the incremental damage that avoids previous problems of this mechanism behaving as an attrition model. This leads to full body breakage of many particles and the creation of significant amount of fine material. The same pilot AG/SAG mill test arrangement is again used but this time using all five of the damage mechanisms. This allows the effect of the incremental damage and the critical interaction of the body and surface damage mechanisms to be demonstrated. Comparison of the predicted and experimental size distributions for the resident rock particles in the mill is performed to provide quantitative validation of the DEM model and its ability to correctly predict size reduction. The predicted final rock size distribution for SAG operation matches the experimentally measured one extremely closely.

2. DEM method

A soft particle style of DEM is used in this modelling as it is in most comminution modelling. This allows collisions between combinations of particles and between particles and 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 (2004, 2009) and the in-house code described there is used in these simulations.

In such 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 as shown diagrammatically in Fig. 1. A linear spring-dashpot model is used here for both the particle-particle and particle-mill collisional force evaluation.

The normal force is given by:

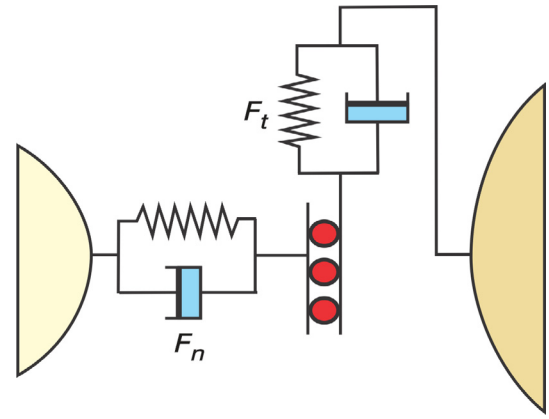


Fig. 1. Diagram of a spring dashpot contact model as used in DEM.

$$F_n = -k_n \Delta x + C_n v_n \quad (1)$$

which consists of a linear spring that provides the repulsive force and a dashpot that dissipates 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:

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

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).

The particles are represented as super-quadric shapes as described and demonstrated in Cleary (2004, 2009). A super-quadric is defined in a canonical frame with Cartesian coordinates (x, y, z) as:

$$\left(\frac{x}{a}\right)^m + \left(\frac{y}{b}\right)^m + \left(\frac{z}{c}\right)^m = 1 \quad (3)$$

The power m is referred to as the blockiness since it controls how sharp the corners and edges of the particle are. The semi-major axes, in the principal directions are a , b and c , with their ratios determining the aspect ratios of the particles as $A_{xy} = b/a$ and $A_{xz} = c/a$. This is a very flexible shape description that allows each particle to have a unique shape with properties selected from user supplied probability distributions for the shape control attributes (including very near to spherical attributes for the balls and suitable representative shapes for the rocks). It also allows the shape of the particles to be changed incrementally throughout a grinding simulation which is made possible by the super-quadric expression (3) being a continuous function of the shape parameters giving continuous variation in shape. This is very important for including shape change from surface damage mechanisms (as shown and described in Cleary and Morrison, 2016).

An algorithm was proposed by Cleary and Morrison (2016) for distributing the energy dissipated in a collision to the five different breakage mechanisms. This uses geometric information of the particle

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