Development of physically based tumbling mill models

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ABSTRACT

Numerical modelling of grinding in tumbling mills is traditionally done with the discrete element method (DEM). The grinding balls are then represented by DEM particles and the mill structure is considered rigid. To include more physical phenomena several numerical methods can be combined. One important improvement is to include the mill structure response, using the finite element method (FEM). The interaction between charge and lining can then be studied in detail. The pulp can also be included using a particle-based continuum method e.g. smoothed particle method (SPH). The strength of SPH lies in modelling of free surface flows and very large deformations and it is suited to model simultaneous fluid and granular flow. Still, the coarse particles (grinding balls) in the charge are suitable to be model using DEM. Each of these methods has their strength and weaknesses, but combined they can successfully mimic the main features of the charge movement. With these numerical tools the complex interaction between the different components of the grinding process; pulp, charge, lining and the mechanical behaviour of the mill, can be studied together. This work will present novel numerical approaches to model, simulate and validate charge behaviour in tumbling mills. These numerical models give possibilities to better understand the physical and mechanical behaviour of particulate material systems during grinding in a tumbling mill. This is important in order to develop and optimise future high-capacity grinding circuits and save energy.
INTRODUCTION

In grinding with tumbling mills many different physical processes occurs e.g. breakage of ore particles, wear of liners/ball media, transport of material and different interactions between materials and fluids. These processes are connected to the charge motion and its interaction with the mill lining. Intermittent in-situ or ex-situ measurements of mill parameters are most often prone to errors and there is often a long time-delay before the acquired data can be fed to the control system. Measurements and monitoring of the milling process is often cumbersome to do and only limited information can be obtained. Numerical methods and simulations can be important tools to understand and predict many different processes. A fundamental issue before trusting numerical results is, however, that the model itself has to be validated against measured data. The complexity of the model and the choice of data to compare against are also important. Wet grinding in tumbling mills is a complex process and has to be simplified in numerical modelling. Here it is important to include as much of fundamental physics as possible for the studied problem. The limiting issue here is that the problems have to be solved within reasonable computational time. Advanced numerical models have to be validated against reality for building confidence and trust. This has led to an increased interest in obtaining an accurate and direct measurement of mill load and the behaviour of the mill charge. Measuring the driving torque and relate it to the process by numerical models might be one possible way to validate, control and optimise the grinding system.

Discrete element methods (DEM) introduced and developed for granular material by Cundall and Strack (1979) have for many years been the main simulation tools used to gain insight into particulate flow processes. In typical DEM mill modelling, mill walls and lifters are represented as rigid bodies that do not deform during collisions. In contrast, this presentation focuses on development of methods for modelling of the grinding process with a combination of structural and particle based numerical methods. To improve predictions of the tumbling mill performance, the inter-particle force law and the contact parameter in DEM simulations was studied by Mishra (2003). One step towards a more physically realistic mill model was taken by Jonsén et al. (2011); they combined DEM with the finite element method (FEM) to model the mill structure and its interaction with the charge. The smoothed particle hydrodynamics (SPH) method together with the finite element method was used in simulations of tumbling mill processes by Jonsén et al. (2012) where hardened SPH-particles represented the grinding bodies. With a SPH-FEM model, structural response and its influence on the charge behaviour could be studied in greater detail. The model gave not only the opportunity to optimize the material selection of the mill structure but also to study the internal workings of the charge. Critical response values e.g., stress and strain can then be identified during the milling process.

Another important step is to include the fluid behaviour in a numerical model of wet milling. A first step to do this was taken by combining SPH-DEM-FEM; see Jonsén et al. (2014). It was shown that the SPH-DEM-FEM model gives the opportunity to study the influence of the mill structure and e.g. pressure and shear stresses in the pulp. The fluid flow properties and its influence on the system response were shown with the model. The validation was done by comparing numerical results with experimental measurements from grinding in an instrumented small-scale batch ball mill equipped with an accurate
torque meter. The choice of model depends on the phenomena that are to be studied. In this work different methods and combined numerical models are presented. All have their strengths and weaknesses and are based on a research strategy of linking modelling with validation.

EXPERIMENTS, MODELLING AND VALIDATION

The combined use of advanced measuring techniques as well as the use of both empirical and fundamental mathematical modelling applied to mineral processes is a key approach to increase knowledge and improved numerical models. When working with numerical modelling of physical systems many factors affects the accuracy of the mechanical response computation, e.g.; the smoothness and stability of the response, the inadequacies and uncertainties of the constitutive equation, the boundary and initial conditions and the uncertainties in the load. Such analyses of the computability of nonlinear problems in mechanics were investigated by Belytschko and Mish (2001).

Mill measurements

Two different mills have been used for experimental measurements. The first is a grate-discharge pilot mill, 1.414 m in diameter and 1.22 m in length, equipped with 12 rubber lifters of square size 0.1 m and a face angle of 45 degrees, see Figure 1a. Steel balls with a diameter ranging between 10-30 mm and a density of 7800 kg/m³ were used.

![Figure 1 Mill experimental setups. a) Pilot mill with rubber lining. b) Lab mill for torque measurements.](image)

The test material, a hematite pellet feed with d50 around 35 µm and a solids density of 5200 kg/m³, was chosen for stable grinding conditions with respect to feed size variations. Feed rate was kept constant at
approx. 1.5 tonne/h. Experiments were run with the mill speed at 73% and 78% of critical speed ($N_c$) for two levels of mill filling ($J = 25\%$ and $35\%$ by volume). The embedded strain gauge sensor measured the load position (toe and shoulder) using the CCM algorithm, proprietary of Metso Minerals. More details regarding the experimental measurements can be found in Tano (2005). The second mill is a laboratory scale ball mill built by SALA (SALA International K706250/1981) and has recently been renovated with new measurement equipment and control logic. The mill has a $\phi 300 \times 450$ mm stainless steel drum with four equally spaced lifters, see Figure 1b. The rotational speed can be set between 10-130 rpm and is maintained by a closed loop regulator. The mill critical rotational speed ($N_c$) is 77 rpm. More details regarding the experimental measurements on the laboratory scale ball mill can be found in Stener (2011). The interaction between the lining and the charge was studied. Driving torque and angular velocity were continuously measured during the experiments. From these measurements power input and work done on the system are easily derived.

**DEM – FEM combined model**

A first natural step of modelling the charge-lining system is by combining DEM together with FEM. Rubber lining material behaviour of the pilot mill is modelled by a hyper-elastic constitutive model. Modelling the physical interaction between DEM particles and the structural parts of the mill is the major challenge in this task. This includes contact search, contact force and friction force interaction for coupling the structural loading to structural response. The validation of this model is done by comparing the experimentally measured and numerically calculated deflection signature for 360° at steady state. This model combination gives insight of how the charge affect the rubber lining.

**SPH – FEM combined model**

The SPH-FEM combination is used to virtually reproduce the pilot mill. Here, the ball charge is modelled with hardened SPH spheres. The problem domain in SPH is represented by a set of particles or points. Besides representing the problem domain, the points also act as the computational frame for the field approximation. Initially, each point is given mass and coordinate information. During calculation, information about spatial coordinate, velocity, density and internal energy is stored in each point. From constitutive relations, stresses and strains are derived. The SPH method is an adaptive Lagrangian method, which means that in every time step the field function approximations are performed based on the current local set of distributed points, see Liu and Liu (2003). As for the DEM-FEM model the validation is done by comparing the measured and numerical deflection signature of a rubber lifter. This model combination gives insight of the pressure and stresses that travels through the charge and its coupling to the mill lining during grinding.

**SPH – DEM – FEM –combined model**

Grinding is usually performed wet to provide a pulp consisting of fine particles mixed with fluid. Here the grinding balls are modelled with DEM and the pulp with SPH. In DEM, the interactions between the SPH-particles are treated as a dynamic process with states of equilibrium developing whenever the
internal forces balance. By tracking the movements of the individual particles, the contact forces and displacement of a stressed cluster of particles are found. Movements result from the propagation through the particle system of disturbances caused by specified wall and particle motions and/or body forces. The speed of propagation depends on the physical properties of the discrete system. Coupling DEM and SPH elements is done using a two way node to node contact algorithm. For DEM-FEM and SPH-FEM a two way node to surface contact is used. To rotate the mill at a constant rotational velocity constraint is used. As the mill rotates the ball charge will induce a load that the driving torque has to overcome. To numerically calculate the torque, a numerical interface is created for the rigid structure of the mill. The validation of this model is done by comparing the experimentally measured and numerically calculated torque signature for a whole turn of the lab mill at steady state. Interesting outcomes from this model are how the pressure and stresses in the pulp vary during different conditions.

RESULTS AND DISCUSSION

An important part of the work is to validate the numerical results by experimental measurements. For the different models two main approaches for validation are used. For the pilot mill, the experimentally measured deformation of a rubber lifter is compared to the deformation in the model. For the lab mill, the experimentally measured driving torque is compared to the numerically predicted torque. For calculating all models the multi-physics program LS-DYNA (LSTC, 2013) has been used.

DEM – FEM pilot mill model

The rotation of the mill induces charge motion, during this motion particle-particle and particle-structure interactions occurs in the mill system. The structure will respond to deformation upon the incoming load from the charge. These deformations will give rise to strains and stresses which are dependent on the material properties of the structure. A snapshot of the von Mises’ stress field for two lifters and the liner in between and during their passage in the charge is shown in Figure 2a. For the fourth lifter passage through the charge, the numerically obtained deflections for a graded respectively non-graded charge is compared with experimental measurements and shown in Figure 2b. Both cases have a similar signature but the maximum peak for the graded charge occurs as the lifter submerges into the charge around 70°. Even though the first and the second peak are almost equally high for the non-graded charge the maximum value is found in the second peak around 115°. The toe angle is around 62° for the non-graded charge and around 48° for the graded charge. The shoulder angle for the non-graded charge is 235° and 220° for the graded charge. The peaks are slightly higher for the graded charge. What is important here is that both simulations show the same 30° separation between the peaks as for the measured signal. This means that the shock waves caused by the lifters hitting the charge are correctly predicted.
Figure 2 DEM-FEM pilot mill model. a) A snapshot of the von Mises' stress field [Pa] for a part of the mill model during its passage through the charge. b) Deflection of the lifter during the fourth passage, solid line represents the response from the measured graded charge and dashed line the non-graded charge response and the dashed and dotted line the graded charge.

SPH – FEM pilot mill model

Compared to a DEM charge model the SPH-FEM model can show mechanical waves travelling in the charge itself and the mill structure. In Figure 3a, a snapshot of the pressure distribution in the charge is shown. As the lifter submerges into the charge, a pressure builds up in front of the lifter. A pressure wave is induced in the charge from the lifter and travels through the charge. As the pressure wave travels through the system, the charge is compressed and unloaded several times. These waves creates fluctuations in the lifter deflection that is shown both in the experimental and numerical studies, see Figure 3b. The highest pressure is found as the lifter enters the charge. There are differences in the signature between measured and simulated results. What is important here is that both simulations show the same 30° separation between the peaks as from the measured signal. This means that the mechanical waves are correctly predicted. The maximum peak values for measured and the simulated signature occurs around 105°. The charge toe angle is 69° for the measured and 65° for the model. The shoulder angle for measured is 202° and 190° for the model charge. The peaks are higher for the model.
Figure 3 SPH-FEM pilot mill model. a) A snapshot of the pressure distribution in the charge. b) Displacement of the lifter during passage, solid line represents the response from the measured graded charge and dashed line the SPH-FEM model with graded charge.

SPH – DEM – FEM lab mill model

A study of the influence on the mechanical response from the pulp is a challenging task. Here the approach is to use SPH to represent the fluid in the mill. The charge and pulp interactions with the mill structure result in a load on the system. To maintain the rotational speed of the mill, the driving torque from the engine will vary with the induced torque from the charge motion. A reduced balls charge consisting of 10.00 kg grinding balls and a fluid volume of 0.85 dm$^3$ is used. The ball charge is named “reduced” since only a 100 mm slice of the mill is modelled. A graded ball charge consists of $\varnothing 9.5$, $\varnothing 12.6$ and $\varnothing 21.3$ mm balls. For the fluid behaviour an Equation Of State (EOS) by Grüneisen (1912) is used. Fluid density and dynamic fluid viscosity is set to 2500 kg/m$^3$ and 267 mPas, respectively with a magnetite suspension. A charge filling of $J_{\text{vol}} = 30\%$ and a rotational speed of $n_c = 66\%$ of critical speed is used. In Figure 4a, a snapshot of the mill model and pressure distribution in the pulp is shown. The model, including a fluid consisting of magnetite suspension, is validated against experimental measurements, see Figure 4b. The SPH method gives opportunity to study, e.g., the pressure in the fluid and how it change over time in the mill. One interesting observation is how the pressure builds up during the entrance and the initial part of the lifter passage through the charge. A snapshot of the pressure in the pulp fully developed for milling with a fluid with properties of a magnetite pulp is shown in Figure 5. The figure shows the pressure distribution in the charge from a cut through the middle of the mill. The highest values are in the region in front of the lifter and close to the mill wall. The combined SPH–DEM–FEM model presented here can predict the classical DEM results, but can also predict responses from the mill structure like, e.g., stress and strain, as well as the pulp liquid flow and pressure.
Figure 4 SPH-DEM-FEM pilot mill model. a) A snapshot of the pressure distribution in the pulp liquid in Pa. b) Calculated and measured torque curves for a mill with magnetite pulp and a graded ball charge.

Figure 5 SPH-DEM-FEM pilot mill model. A snapshot of the pressure distribution [Pa] in a magnetite pulp liquid. Pressure builds up in front of the lifter and close to the mill wall.
All parts of the mill system will affect the model response, and a SPH-DEM-FEM model gives several new opportunities to study the influence of the mill structure and for example pressure and shear stresses in the charge and lining. This interaction deforms the lining, and since deformation is coupled through a constitutive relation, stresses, strains and mechanical waves for the mill structure can be obtained. For the SPH-FEM model the lining behaviour also can be studied, but the main purpose is that the loading of the charge and the propagation of mechanical waves in the charge and the whole mill system can be obtained. As shown in Figure 3a the pressure distribution in the charge can be found. The SPH-DEM-FEM mill model includes the behaviour of a pulp and its coupling to the grinding balls and mill structure. This can be used to study, e.g. pressure in the pulp and mechanical waves propagating in the whole mill system.

CONCLUSIONS

Modelling and simulation of tumbling mills can be improved and new combinations of numerical methods give interesting results. The choice of model combination depends on what information the user desire from the studied system. The experimental methods to accurately measure lifter deformation behaviour and torque during milling enable the comparison of the numerical models directly against measurements. Validation studies with numerical models for pulp and charge, but also studies on how the various parts of the models are connected is a key part to obtain trustworthy models.

To include the mill structure response, the charge and the pulp in the numerical models gives more information regarding mill system and may result in better correlation between experimental measurements and numerical models. The SPH-DEM-FEM tumbling mill model presented here is one of the first approaches to include the pulp and study its response. Still, there are several challenges for modelling the grinding process in a physically correct manner. The coupling between SPH, DEM and FEM is interesting and needs to be further studied. Here, the pulp behaviour and interaction with grinding balls and mill lining is a challenge. The free surfaces and the method to include pulp in a good manner are important to study.

ACKNOWLEDGEMENTS

For financial support of the project ValidMill, the Hjalmar Lundbohm Research Centre, LKAB and Boliden Mineral AB are gratefully acknowledged.
REFERENCES


