DEM-BASED SIMULATION FRAMEWORK AS A TOOL TO PREDICT GRINDING IN AG/SAG MILLS[1]

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Abstract

With the growing need to comminute Brazilian Itabirite iron ores to fine sizes for pellet production, the importance of grinding has risen in recent years. Given the benefits of SAG and AG mills in comparison to competing technologies, a number of projects are considering their incorporation in the new plants. Questions still exist, however, on the level of confidence that can be met in their design, considering how unusual these iron ores are in comparison to the ones normally ground in these machines. Empirical and phenomenological models of SAG and AG have been widely used in the design of these mills. However, in spite of their success, these models fail to describe the details of both the grinding environment and of the breakage mechanisms that act inside the machine. Recognising these and other challenges, a new mechanistic model framework has been proposed which overcomes the limitations of currently used models, by coupling the population balance model, the discrete element model (DEM) to functions that describe internal classification at the mill grate. The paper describes the model framework, demonstrating how it can address appropriately effects such as mill speed, mill filling and size distribution, on the response of a pilot-scale SAG mill. It is envisaged that the model, in the future, will become a useful tool to predict the behaviour of ores in these mills under different operating conditions, prior to running pilot plant tests.

Key words: SAG milling; Grinding; Mechanistic modelling.

SIMULAÇÃO BASEADA EM DEM COMO UMA FERRAMENTA PARA A SIMULAÇÃO DE MOINHOS AG E SAG

Resumo

Com a necessidade crescente da cominuição de minérios Itabiríticos brasileiros até granulometrias finas para a produção de *pellet feed*, a importância da moagem tem crescido em anos recentes. Tendo em vista os benefícios de moinhos AG e SAG em comparação com outras tecnologias, vários novos projetos estão considerando a sua incorporação nas novas usinas. Questionamentos ainda existem, entretanto, sobre o nível de confiança que pode ser atingido no seu projeto, principalmente tendo em vista quão pouco usuais esses minérios de ferro são em relação àqueles normalmente moídos nesses tipos de moinhos. Modelos empíricos e fenomenológicos de moinhos SAG e AG têm sido amplamente usados no projeto de novos moinhos. Entretanto, apesar do seu sucesso, esses modelos são incapazes de descrever os detalhes do ambiente de moagem e os mecanismos que ocorrem no interior do equipamento. Reconhecendo esse e outros desafios, um novo modelo mecanicista foi proposto que supera as limitações dos métodos atualmente usados, pois combina o modelo do balanço populacional, o método dos elementos discretos (DEM) a funções que descrevem a classificação interna que ocorre no diafragma desses tipos de moinhos. O artigo descreve a modelagem proposta, demonstrando como ela pode permitir descrever efeitos como o da frequência de rotações do moinho, enchimento e distribuição granulométrica da alimentação na resposta de um moinho operando em escala piloto. É previsto que o modelo, no futuro, irá se tornar uma ferramenta ponderosa para investigar o comportamento do minério nesses moinhos operando sob uma variedade de condições, antes de recorrer a ensaios em escala piloto.

Palavras-chave: Moagem; Moagem SAG; Modelagem mecanicista.

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1 INTRODUCTION

Predictions of full scale operation in mineral processing are often challenging using small-scale information. This is particularly critical in Greenfield projects, since sample availability is minimal and important decisions regarding circuit configuration and equipment dimensions and power have to be made. It is arguable that in the case of the ball mill this is not, in general, such a challenging task, given that reasonably good predictions of full-scale operation can be made on the basis of information available from small samples using either Bond´s empirical method or the population balance model (1,2). The result is that running pilot plant tests is certainly not recognised to be a requirement in every ball mill design, although challenges remain in applications involving grinding of some Itabirite ores (3).

In contrast to that, there is little argument that autogenous (AG) and semi-autogenous (SAG) mills represent important challenges in mill design, particularly in the case of Greenfield projects. Whereas in machines such as ball or rod mills the media that is responsible for transferring the mechanical energy to particles remains relatively invariable with time, with a mechanical response that is largely independent of the ore characteristics, this is not the case in SAG and AG mills. In these mills, the feed ore characteristics have a dramatic effect on both the outcome of the process and on the mechanical response of the media, since the ore makes up for either part or the totality of the grinding media.

In spite of this challenge, a number of standard tests (SPI, SAGDesign, SMC and others) have been proposed with the aim of providing information that can be used in the design of SAG and AG mills (4). While relevant in characterising ore variability for circuit design, predictions do not match the level of confidence exhibited by Bond's traditional method when applied to ball mills. Alternatively, investigations have also been conducted with the aim of developing mathematical descriptions of comminution in SAG and AG mills using the population balance model (5,6). Although with a greater level of detail in their description of material characteristics and equipment performance, these tools have not evolved to the level that allowed reaching confident predictions of full-scale mills solely from data collected in the laboratory. The alternative normally used has been to conduct extensive pilot plant campaigns, which are, however, very costly, besides requiring large volumes of sample, which are often not available.

There is little doubt of the value of improved mathematical models of SAG and AG mills to help keep pilot plant tests at a minimum or, perhaps, to allow the design of mills with no piloting at all, using data only from bench scale testing. This objective has certainly not yet been reached using either the empirical or the phenomenological (population balance-based) models proposed in the past. Fortunately, the important advances that have been made over the last 20 years in both characterising and modelling material breakage response of ores, and in simulation of media motion in mills using the discrete element model (DEM), now offer a unique opportunity to evolve SAG/AG mill modelling to an entirely new level. Through a detailed understanding of ore breakage and of the mechanical environment, coupled to a microscale population balance model framework, a future in which the performance of mills of different dimensions operating under a variety of conditions can be predicted using data collected in the laboratory using samples weighing less than 100 kg can be envisaged.

The expansion of the Brazilian iron ore industry and the limited availability of high-grade deposits from which lump ore and sinter feed could be produced, are leading to a step change in grinding requirements in the industry, with massive focus toward the production of pellet feed. As such, size reduction has gained significant importance in the new iron ore projects. Among the different options available for the design engineer are autogenous (AG) and semi-autogenous (SAG) mills, which have the great benefit of simplifying the plant flowsheet, reducing CAPEX and metal consumption associated to wear. The challenges associated to it, however, are the lack of experience with the technology in the iron ore industry in Brazil and the limited use, in the past, of geometallurgical information in plant operation, which will both have to change quickly if the technology is to be applied successfully.

The present work describes the modelling approach being proposed at UFRJ/COPPE to describe comminution in SAG and AG mills, which can be a valuable tool in improving confidence in design of new iron ore plants using AG/SAG grinding and reducing the risk of not meeting design performance.

2 MODEL OVERVIEW

The model is essentially a particular case of the general microscale comminution model proposed by Carvalho and Tavares(7) which was proposed to include all the relevant microprocesses in SAG and AG mills. A schematic representation of the model is shown in Figure 1, which demonstrates that the model decouples material from machine contributions to the outcome of the process. Ore breakage characteristics are described in great detail using a combination of testing methods, which allow describing body (volume) breakage resulting from both self-impacting particles and by the crushing action of grinding media, as well as surface breakage. Ore characteristics also influence the contact parameters used to describe the DEM simulations, besides the size distribution of the charge and density. The discrete element method allows describing the influence of particle and ball size distribution, mill size, liner configuration and rotation speed on frequency and magnitude of the collisions involving particles contained in the charge. Tools such as computational fluid dynamics (CFD) and smoothed particle hydrodynamics (SHP) can then aid in describing the flow of slurry through the media and discharging through the grates.

Figure 1 shows that simulation involves a number of couplings among the techniques. For instance, simulation starts by running the DEM using either an estimated guess of the steady-state contents of the mill or the size distribution of the feed, besides the ball charge. When steady-state is reached (after several seconds) in the DEM simulation, the collision energy spectra for each pair of type of bodies in contact (ores or steel media) are captured and the data are feed into the microscale population balance model (MPBM). The dynamic MPBM equations are then solved, which account for the continuous introduction of new feed, resulting in a new size distribution of ore contained inside the mill. At this point, an appropriate description of the discharge (if available, mechanistic) is applied to the mill contents, allowing for a selective discharge of particles contained in different size and composition classes. If the charge contents have changed significantly since the previous DEM simulation, then a new DEM simulation of the new mill contents must be conducted. Collision energy spectra from this DEM simulation is then fed back to the MPBM, completing the cycle, which should be repeated until steady-state grinding conditions are reached. This entails a complete dynamic simulation of the AG/SAG mill. Evidently, the AG/SAG mill can be simulated in conjunction with a trommel, a screen and/or a crusher used to reduce the size of pebbles that leave the pebble ports, provided that appropriate quantitative descriptions of these are available.

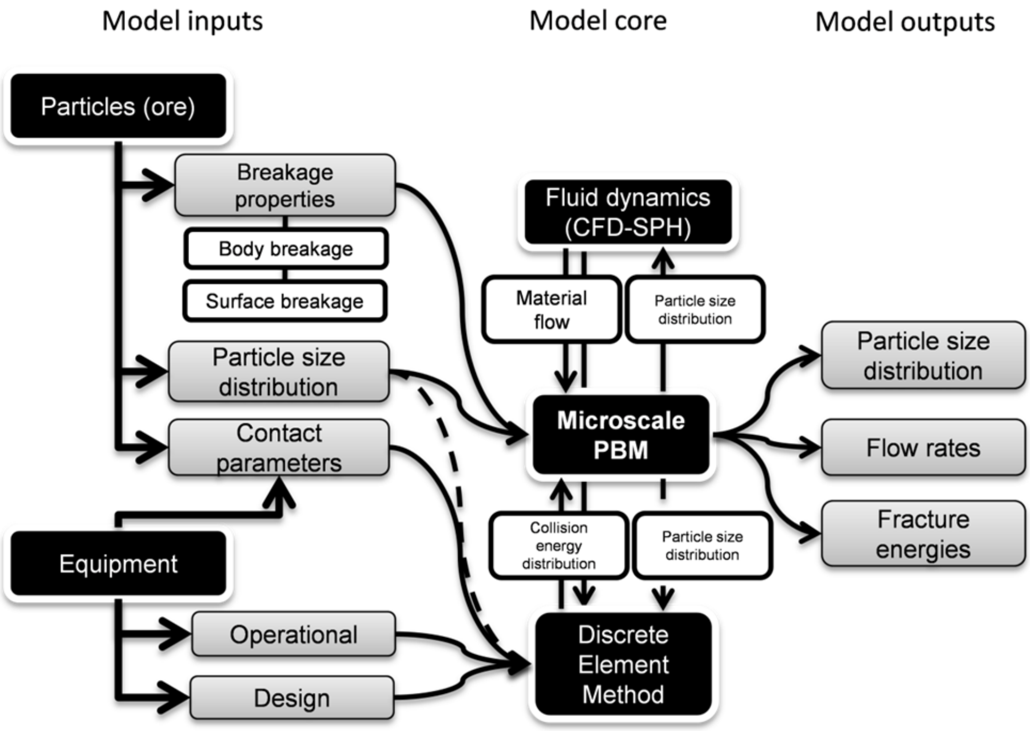


Figure 1. Proposed AG/SAG model structure.

Therefore, perhaps the greatest difference between the microscale model applied to AG/SAG mills and to ball mills(8) is related to the fact that in the former the mechanical environment is continuously changing with time, since the ore corresponds to a significant part, if not the totality, of the charge. Another important difference is related to the greater contribution of surface breakage in AG/SAG mills in comparison to ball mills, as well as the greater relative importance of the shear component of the collisions in these mills.

The key advantage of the modelling approach proposed is that the influence of several variables in AG/SAG milling can be described free of empiricism, given the capability of DEM to describe the influence of mill liner profile, diameter, length, mill speed, feed size and ball size distribution on the mechanical environment that is responsible for breakage. Further, as long as different components, which can be rock or ore types, can be identified in the feed and characterised separately, then the model can be used to describe grinding of multi-component feeds.

In the present work, breakage mechanisms are classified as body breakage and surface breakage. In addition, a collision event in which a particle does not break, but its strength is reduced by accrual of damage is also described appropriately (9). Body breakage is further classified as being the result of either one or two-point impact. In the former, the particle is broken as the result of the crushing action by other coarser particles, steel grinding media or either one of them impacting against a liner. In one-point impact, also called self-breakage, it results from the collision of the particle itself against other particles, grinding media or the mill liner. Detailed models of the different breakage mechanisms have been proposed and are presented elsewhere.(10,11)

Breakage events occur as the result of the linear and angular motion of grinding media in relation to each other, resulting in contacts that vary from head-on collisions to the shearing action of grinding media rolling over each other inside the charge. In this context, information of the mechanical environment that is relevant to describing milling at a microscale level include the type, frequency and magnitude of collision events involving both balls and autogenous media. In the past, insight into these could only be gained through extremely careful and tedious experiments(12), through which the history of collisions of individual balls was followed over a period of time. Fortunately, since the 1990s it has been possible to simulate the motion of media in ball mills through the application of the discrete element method (DEM) (13). DEM is a simulation tool which uses Newtonian physics coupled with appropriate contact models and powerful computational codes to allow the prediction of the magnitude and frequency of collisions that occur in a mill.

In the present work DEM media motion simulations have been conducted using the software EDEM® (DEM Solutions, Edinburgh, UK). The no-slip Hertz-Mindlin contact law has been used to describe the contacts among grinding media and between them and the mill shell.

It is proposed that DEM simulates the motion of both steel balls and particles which are larger than the grate opening in the mill. These represent the material that makes up for most of the charge content in the mill, and certainly nearly the totality of the particles responsible for transferring the energy that causes breakage. Particles which are finer in size, called ‘sub-DEM particles’ (14), do not appear explicitly in the DEM simulations, since their presence would make computing prohibitively time-consuming. The mass balancing of these particles, ensuring that material will neither appear or disappear in the simulations, will be carried out within the MPBM.

The first step toward collecting appropriate data from DEM simulations is to choose appropriate parameters to describe every type of contact that occurs in the mill. A summary of the constants used to describe ball-ball and ball-wall contacts in DEM is presented elsewhere (11). Simulations are then run and, after steady-state conditions have been reached, the dashpot energies (energy loss) for every pair of contacting bodies are computed. This gives a total of k collision energy spectra for the different classes of contacts.

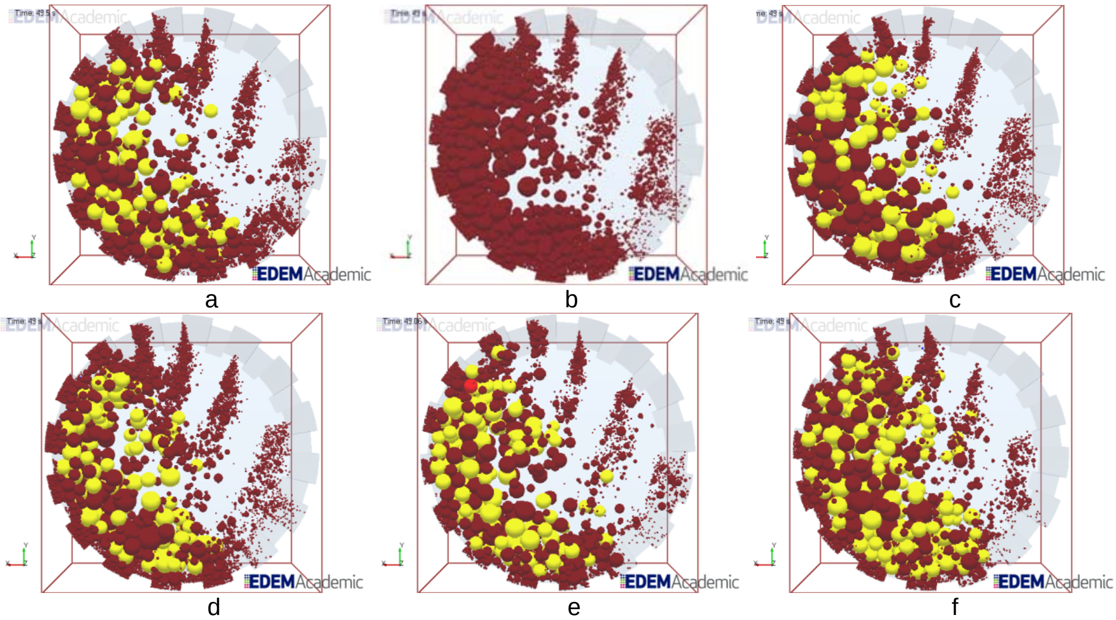
Particle capture and the energy distribution in the collision events has been described by models presented elsewhere (11,15).

Considering that mill contents in high-aspect ratio AG/SAG mills can be well described assuming that they are perfectly mixed, the only remaining unknown element required for modelling these mills is the discharge (also called internal classification) description. Although important advances have been made in its mechanistic modelling using tools such as CFD and SPH (16), these descriptions are not yet readily available to incorporate in the present mechanistic model. Fortunately, in the case of pilot-scale mills which have been crash-stopped (14) and the entire contents sized, the size-dependent discharge rates can be estimated directly using the mill load and mill discharge size distributions.

3 RESULTS AND DISCUSSION

3.1 Collision Energy Spectra

As previously discussed, DEM provides essential pieces of information for simulating AG and SAG mills using the proposed mechanistic framework. In order to demonstrate the relevance of such information, DEM simulations have been conducted for a pilot scale mill with 1.8 m of diameter (6´x2´) operating under a range of conditions grinding -150 mm copper ore. Snapshots of the DEM simulations are presented in Figure 2. Figure 3 shows the different size distributions of the mill hold up in the tests, measured after crash-stops of the pilot mill, whereas Figure 4 shows the different ore and ball charges used in the tests.



a b c d e f

Figure 2. Snapshots of DEM simulations of the pilot SAG mill at the 76% of critical speed for cases a to e and 72% for case f. Balls are colored in yellow and ore particles in brown.

In order to convey the information on the collision geometry to the MPBM, it is necessary to define each of the collision classes. A collision of a given class contains information about the particles involved in that type of collision, in terms of material (ore, balls, liner) and size. A detailed assessment of these collision classes is available elsewhere (11). In the present work and for illustration purposes, collision energy spectra for all contacts in the mill for each simulation case displayed at Figure 2 have been combined and results are shown in Figure 5, which shows the significant variations encountered, which will lead to differences in predictions using the MPBM.

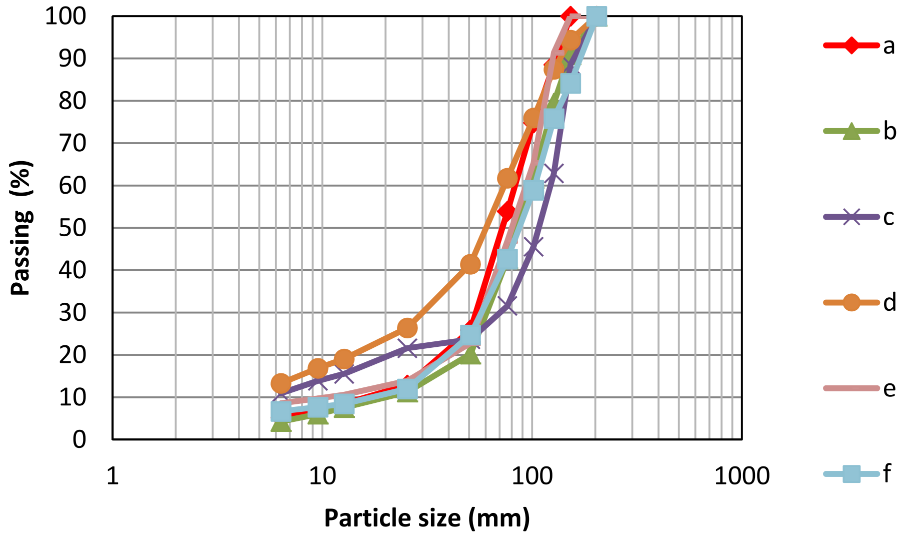


Figure 3. Size distributions of the ore contents in the mill for the six simulations depicted in Figure 2.

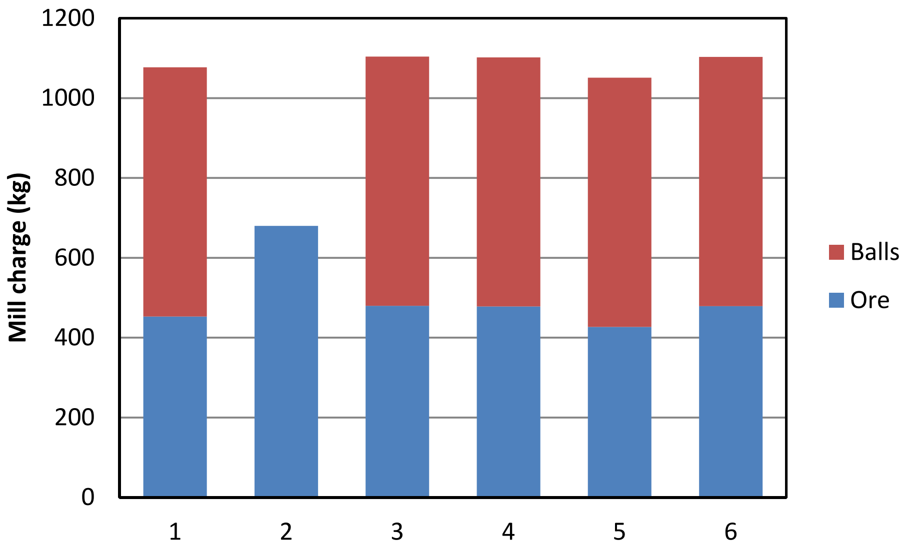


Figure 4. Measured ore and ball charges measured after crash-stops of the pilot scale tests simulated in Figure 2.

A summary of simulation results is presented in Figure 6, which shows that milling conditions simulated resulted in a range of powers, collision energies and frequencies. For instance, a comparison of simulations “d” and “f” shows that, although these two grinding conditions resulted in, approximately, the same net power, simulation “d” yielded lower collision energies (80th percentile), but a much higher frequency than simulation “f”. These differences will likely result in a difference response in grinding, in spite of a common power draw.

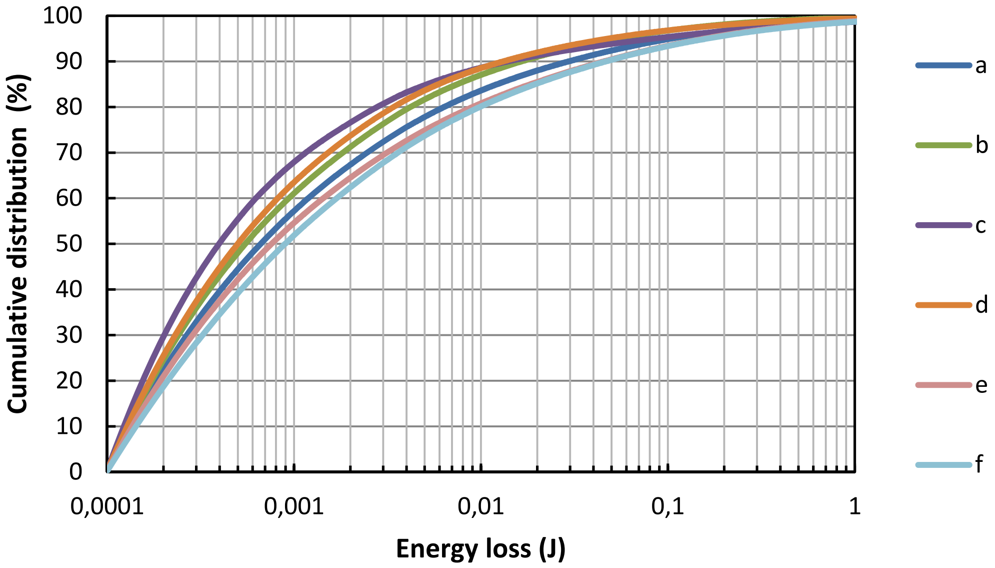


Figure 5. Collision energy spectra for simulations depicted in Figure 2.

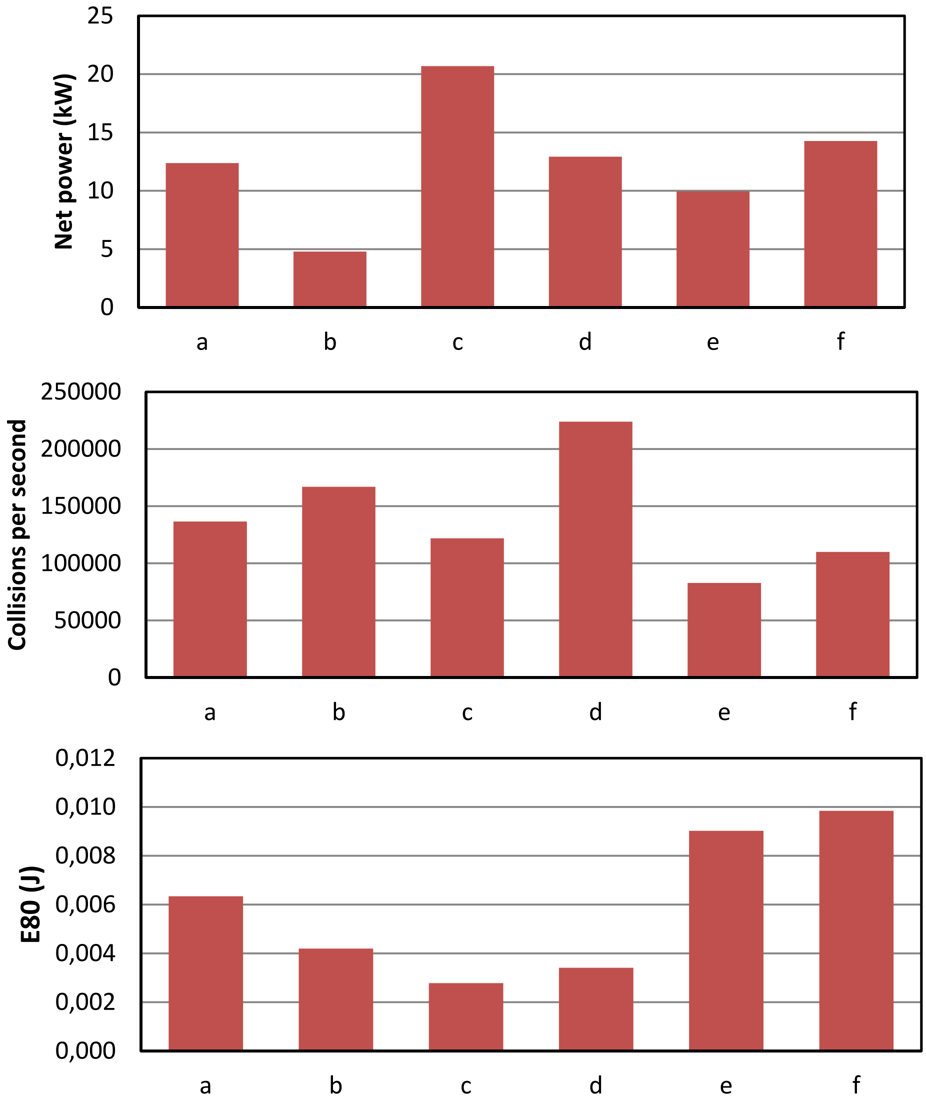


Figure 6. Results fom DEM simulations: net mill power (top), collision frequency (middle) and the 80th percentile of the collision energy.

3.2 Breakage Rates

In order to demonstrate the potential of the MPBM approach to describe comminution in a SAG mill, a pilot plant mill grinding the copper ore was simulated. The mill has 1.8 m of diameter (6´×2´) and was operated at 75% of critical speed. The mill filling is 10% of steel balls, with a top size of 150 mm, and 15% of ore, and the mill was drawing 13.7 kW of power, corresponding to simulation “a” in Figure 2.
Besides the DEM simulations, the MPBM also requires detailed data characterizing the ore breakage characteristics(10,11). Perhaps the most significant information describing the breakage response of the ore is the size-dependent fracture energies, measured using the impact load cell (10). Typical results for the copper ore simulated are presented in Figure 7, being compared to data from two other Brazilian iron ores. It is evident that the iron ores, notably the Itabirite, are significantly softer than the copper ore, which should lead to a dramatic effect in their response to grinding in AG and SAG mills.

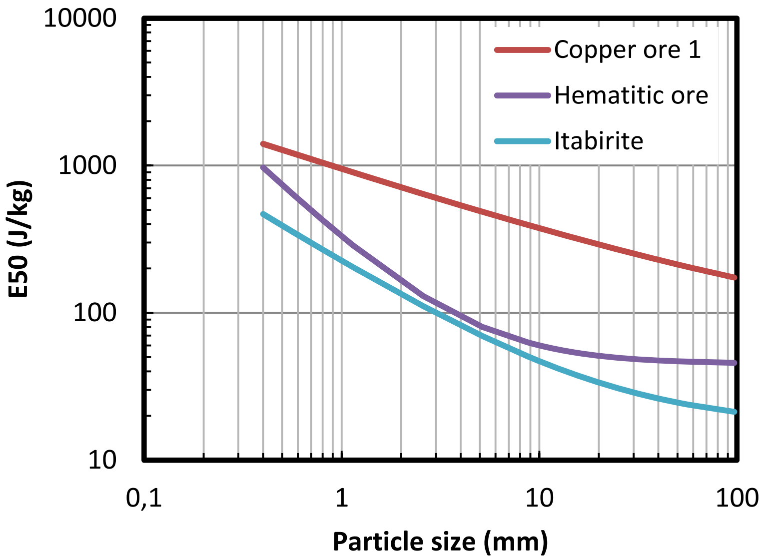


Figure 7. Variation of the median particle fracture energy of selected ores from Brazil as a function of particle size.

Data from the DEM collision energy spectra and material breakage characteristics were then fed into the MPBM equations (11), solving them numerically for a given lapse of time. In order to illustrate the model response, the apparent breakage rates were calculated. Figure 8 (right) shows the apparent breakage rates as a function of particle size, which resemble typical results shown in the literature (5), in which fine particles have low breakage rates, reaching a maximum at about 10-20 mm, dropping for particles at about 40 mm in size, then raising again for particles all the way up to 150 mm in size.

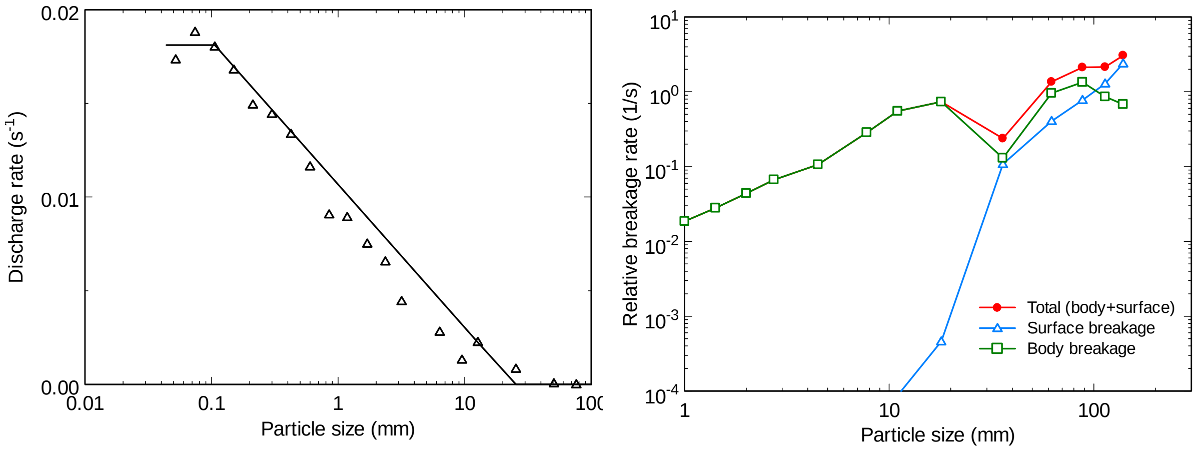


Figure 8. Discharge function for a pilot-scale SAG mill (left) and breakage rates for grinding copper ore in the pilot SAG mill displayed in Figure 3 (left).

Figure 8 (right) also shows the contributions of body and surface breakage on the apparent breakage rates for the different particle sizes. Whereas surface breakage plays a very important role in breakage of the coarsest particles contained in the hold-up, it becomes of limited importance for finer particles contained in the charge. In every case, it is likely that particles are often stressed with insufficient amounts of energy to cause breakage in each collision event, so that particles are progressively damaged and only then, broken.

The coupling approach used in modelling AG/SAG mills proposed in the present work allows the optimisation of computer processing time for the different tools used. For instance, the time step used in integrating the equation of motion for each element in DEM is in the order of 10^{-5} s, whereas the time step used to simulate the microscale population balance (MPBM) equations varies between 0.01 and 0.1 s. The equations of the MPBM can be solved for periods as long as a few seconds, until a new DEM simulation of the charge is required.

One strength of the modelling approach proposed is that multi-component feeds can be appropriately described. The model has the potential to predict the concentration of the tougher component within the mill contents during mill operation, as well as the different size distributions of the different components in the mill discharge. Work is ongoing in the authors' laboratory to demonstrate this application.

Since the model describes the variability in material response to breakage both as a single-component or a multi-component feed and also gives, as output, the fracture energy distribution of the discharge material (Figure 1), it can potentially predict the preferential discharge of tougher pebbles that will be typically fed to recycle crushers.

Given the semi-empirical nature of the discharge model, its application is limited to cases whenever a discharge function is available from experiments. In such cases, the fitted discharge function could then be, in principle, used to predict grinding performance of the mill under other sets of conditions. Whenever data from the mill discharge function are not available, the model could still be used to provide insights into mill operation, such as to predict the amenability of the ore to build up appropriate media charge (without overfilling). Unfortunately, without a sufficiently accurate discharge model, the present modelling approach will be unable to predict with the required level of confidence the flow rate of the mill discharge.

4 CONCLUSIONS

A mechanistic model framework to describe comminution in SAG/AG mills has been proposed. It is based on the combination of three contributions: firstly, detailed mathematical models of body and surface ore breakage; secondly, descriptions of the mechanical environment within the mill provided by DEM media motion simulations; and finally, appropriate descriptions of the mill discharge. It has been applied to a pilot scale mill, yielding predictions of apparent breakage rates which follow the typical size effect found in the literature.

The application of this model to Brazilian iron ores, which often are significantly softer than the ores commonly ground in these mills, will enable identify challenges and opportunities for grinding these ores in AG and SAG mills.

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