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New population balance model for predicting particle size evolution in compression grinding

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ABSTRACT

Population Balance Models (PBM) are widely used to predict the evolution of the particle size distribution during various grinding processes, such as ball milling. They represent breakage through the definition of particle destruction and fragments generation rates. Their application to compression grinding (HPGR, vertical mills…) has been limited, due to the complexity of interactions between particles of different sizes.

In this work, we present a new PBM approach for compression grinding. Complex interactions between size classes are represented in a simplified manner by making particle destruction and fragment generation depend on the bed porosity. Model is tested by confrontation to an extensive collection of experimental results on a piston-die cell, on three different materials (cement clinker, limestone, and quartz). When properly calibrated with preliminary tests, the model is able to predict the evolution of the particle size with accuracy, for any starting grain size distribution and any load.

1. Introduction

Compression grinding equipments, such as high pressure grinding rolls (HPGR) or vertical mills, have been now in service for several decades, following the invention of the HPGR by Schönert, 1988. HPGR, vertical mills, but also Horomill (Cordonnier, 1994), despite their differences in terms of geometry, are all based on the same physical principle: the relatively slow compression of a granular bed. Such equipments are now operated worldwide in the mineral and cement industry (Kowatra, 2004). Those mills are reported to save up to 40% of the necessary energy input as compared to ball mill grinding, and thus represent a huge technological improvement, despite remaining process control problems for some applications, most notably with fine powders (Schönert, 1988; Fuerstenau and Abouzeid, 2002; Fuerstenau and Abouzeid, 2007; Wang and Forrsberg, 2003; Aydogan et al., 2006; Musa and Morrison, 2009).

We focus here on a well-explored laboratory test to represent the compression grinding process, the piston-die cell. In this test, a small sample of materials (100 g in our case) is put in a cylindrical chamber. A piston is then forced on the materials with a press, to reach levels of pressure in the material of the same magnitude of what is encountered in the industry (up to 100–200 MPa). The test has been extensively used in the literature to model the more complex industrial setting (for example (Aziz and Schönert, 1980; Fuerstenau et al., 1996), or more recently (Oettel et al., 2001; Hosten and Cimilli, 2009 or Dundar et al., 2013)). Most recently, Kalala et al., 2011 address several aspects of HPGR/compression cell equivalence, such as energy draw or mimicking in the cell side effects on HPGR.

The object of this communication is to present a new, semi-empirical model to represent the evolution of the particle size distribution at the material level during the compression grinding process. More precisely, we exploit the alleged regularity of the stress and strain field in the piston-die cell to observe the behavior of an elementary unit of material, and we want to correlate data such as stress, deformation or relative density with fragmentation level. Such a tool would be a key ingredient for detailed modeling of compression grinding equipments, using techniques such as DEM modeling, for instance.

For this, we rely on the use of a Population Balance Model (PBM), a type of model where particle size distributions are divided into size classes. Fragmentation is then represented through the transfer of mass between those size classes. PBM has been extensively used to represent ball milling, since the seminal works of Austin and Luckie, 1972, Whiten, 1974. Reviews on the application of this type of model in this field of application can be found in Benzer, 2000 or Hashim, 2004.

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Given the development of the usage of compression technologies in the industry on one hand, and the wide usage of PBM in the modeling of ball mill circuits on the other, it is surprising that very little attempts have been made to apply PBM to compression grinding. In ball milling, the modeling is greatly facilitated by the possibility to represent the process through linear relations. Breakage rates, for instance, can be considered as constant functions of time, unaffected by the evolution of the grain size distribution (at least in a wide range of fineness).

This is no longer possible in the case of compression grinding. First, there is no obvious definition of "time", in compression grinding (should we consider the evolution of the applied load? the increase of material density?...). Even more important, the breakage behavior of the particles is deeply affected by the granular environment (contact number, bed density...). Any attempt to represent the breakage of the particles in compression through PBM is bound to take into account those non-linearities.

Such an attempt to formulate a general non-linear PBM model, taking into account particle interactions, is made by Bilgili et al. in Bilgili et al., 2006. It is applied to compression grinding in Bilgili and Capece, 2012. The general model is very complex, and to apply it to compression grinding, the authors need to apply disputable simplifications (for instance, they neglect secondary breakage, i.e. the breakage of particles that themselves come from an initial breakage event). Even in this simplified form, the model seems to have had limited application in practical cases.

Most recently, Dundar et al., in Dundar et al., 2013, used a piston-die test to calibrate a PBM for HPGR crushing. The model relies on important simplifications of the actual process, but is simple to implement and is the first of its type to actually model the real industrial process. Incidentally, it brings elements in favor of the modeling of compression grinding through the piston-die test.

Another attempt to represent the evolution of particle size, though not through the PBM approach, has been developed by Schönert and his team in Liu and Schönert, 1996. The model is based on an "energy split function" that divides the total energy input between size classes. The particle size evolution in each class is then considered to be similar as the one observed in a monodisperse test for the same energetical input.

Attempts have also been made to apply PBM directly at the process level. Models then do not necessarily represent precisely what actually happen to given sample of material as a function of load, but the comminution effect of the industrial device taken as a whole.

Fuerstenau et al., 1991 developed a method to adapt PBM models in the case of HPGR operation. Energy input is used as the "time" variable, and non-linearities are taken into account by introducing a "retardation effect" with increasing pressure, illustrating increased dissipation rate with increasing pressure. The model successfully reproduces the experimental results. More recently, Hinde and Kalala, 2009 proposed a broader correlation, still for HPGR, between starting and final granulometries, using a general law exploiting the energy input to describe the amount of fragmentation provided by the machine.

Such models are certainly useful tools in terms of process control, as they allow to represent the behavior of a given equipment (here, mostly HPGR) as a function of operating parameters (power draw, for instance). However, they are not designed to precisely represent the mill heterogeneities and their potential influence on the global process. This difference is most crucial when considering more complicated geometries than the classical HPGR system, such as in vertical mills or Horomills.

One remaining difficulties with those existing models, both at the material and at the process level, is that they cannot be considered as fully predictive. They do reproduce well the experimental results, sometimes up to the final industrial process. But some parameters need to be numerically adjusted for every test, and prediction of results under a new set of conditions (pressure and starting size range) is not possible. The model can then considered at best as a numerical description of what is happening during the test.

The present model focuses on the preliminary calibration for a given material, on a given set of experiments. As we see it later in this presentation, once the calibration is done, the model can safely be applied to this material, for any starting granulometry, for any applied pressure. We believe this predictive power is one of the major characteristics for such a model to be one day applied in a broader context.

A predictive model is also a condition if we want to provide a full numerical modeling of compression grinding. Material flow in roller compaction or HPGR grinding can for instance already be modeled through Finite Element Modeling (FEM) simulation, originally in 2D (Cunningham, 2005; Michrafy et al., 2011), and now in 3D (Cunningham et al., 2010; Michrafy et al., 2011). PBM model would allow to couple the informations from such FEM modeling with comminution, constituting a powerful tool for the understanding of compression grinding equipments of any geometry.

2. The non-linear PBM model

In PBM, the evolution of grain size distribution is modeled through the transfer of material between size classes, through a linear relationship first formulated by Epstein, 1947, and first applied to grinding (of coal) by Broadbent and Calcott, 1956. In a matrix form, the particle size distribution at instant $n+1, \underline{\boldsymbol{F}_{n+1}}$ depends of the size distribution at $n, \underline{\boldsymbol{F}_n}$ through relation (1):

$$\underline{\boldsymbol{F}_{n+1}} = \underline{\underline{\boldsymbol{T}_n}} \cdot \underline{\boldsymbol{F}_n} \tag{1}$$

With $\underline{\underline{\boldsymbol{T}_n}}$ being defined through (2):

$$\underline{\underline{\boldsymbol{T}_n}} = \underline{\underline{\boldsymbol{I}}} - \underline{\underline{\boldsymbol{S}}} + \underline{\underline{\boldsymbol{B}}} \cdot \underline{\underline{\boldsymbol{S}}} \tag{2}$$

$\underline{\underline{\boldsymbol{I}}}$ is the identity matrix.

$\underline{\underline{\boldsymbol{S}}}$ is a diagonal matrix, called selection matrix. Its ii term describe the probability that a particle from class i gets broken between n and $n+1$.

$\underline{\underline{\boldsymbol{B}}}$ is a triangular matrix, call grinding or repartition matrix. Its term ij describe the proportion of fragments of size j when a particle of class i is broken.

So when we consider the terms in Eq. (2), we see that the first term characterizes mass conservation, the second the disappearance of a particle from its size class when broken, the third the repartition of the fragments between the smaller size classes.

Baxter et al., in Baxter et al., 2004, formulated a general way to include non-linearities in this relationship (3):

$$\underline{\boldsymbol{F}_{n+1}} = \underline{\underline{\boldsymbol{T}_n}}(\underline{\boldsymbol{F}_n}) \cdot \underline{\boldsymbol{F}_n} \tag{3}$$

Of course making the matrix $\underline{\underline{\boldsymbol{T}_n}}$ a function of the full size distribution $\underline{\boldsymbol{F}_n}$ would need to a very complex formulation. In this model, our essential assumption is to simplify expression (3) by assuming $\underline{\underline{\boldsymbol{T}_n}}$ is a function of the granular material porosity, ϕ (or symmetrically, the relative density $1-\phi$). In other words, we assume that the complex effect of the granular environment (the number of contacts, the distribution of the load pattern...), can be summarized through the packing density alone.

Based on such an assumption, the selection matrix $\underline{\underline{\boldsymbol{S}}}$ can be directly determined from experimental tests. Indeed, the disappearance rate of the top size class as a function of ϕ can be calculated from a set of tests on originally monodisperse size fractions.

A first estimation for the repartition matrix $\underline{\underline{\boldsymbol{B}}}$ can also be obtained experimentally, by considering tests on monodisperse fractions, for a low applied pressure. In this case, the extent of