Optimization of Comminution Circuit Throughput and Product Size Distribution by Simulation and Control

Quarterly Technical Progress Report

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Abstract

The goal of this project is to improve the energy efficiency of industrial crushing and grinding operations (comminution). Mathematical models of the comminution process are being used to study methods for optimizing the product size distribution, so that the amount of excessively fine material produced can be minimized. This will save energy by reducing the amount of material that is ground to below the target size, and will also reduce the quantity of material wasted as "slimes" that are too fine to be useful. This will be accomplished by: (1) modelling alternative circuit arrangements to determine methods for minimizing overgrinding, and (2) determining whether new technologies, such as high-pressure roll crushing, can be used to alter particle breakage behavior to minimize fines production.

In the first quarter of this project, work was completed on a basic comminution model that will be used to carry out the subsequent project tasks. This phase of the work was supported by the Electric Power Research Institute, as their cost-share contribution to the project. The model has been implemented as an Excel spreadsheet, which has the advantage of being a very portable format that can be made widely available to the industry once the project is completed.

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Introduction

Comminution is any process where particles are crushed, ground, or otherwise broken to reduce their particle size. Crushing and grinding of various feedstocks is a critical operation in mining, as well as in a range of other industries. It is necessary to liberate valuable minerals from waste constituents so that they can be separated, and for producing products with the correct particle sizes for use. However, comminution is both energy-intensive and expensive, with tremendous room for improvement. Comminution operations in 1981 used 32.7 billion kilowatt-hours of electric power, which approached 2% of total U.S. electric power consumption that year, and so improvements in the efficiency of these processes would be of great economic significance. However, optimization of full-scale comminution processes by direct experiment is difficult and expensive because of the cost of modifying and operating the circuits to conduct these experiments. Mathematical simulation of the process is therefore necessary in order to make a preliminary determination of the most promising routes for optimizing the processes

Executive Summary

Traditionally, model-based optimization of comminution (crushing and grinding) has concentrated on maximizing throughput and energy efficiency, so that the maximum amount of material can be processed with the minimum amount of equipment. However, no attempts have been made to use modelling to reduce the quantity of waste fines and “slimes” produced. The goal of this project is therefore to use comminution modelling to study methods for optimizing the product size distribution, so that the amount of excessively fine material produced can be minimized. This will be accomplished by: (1) modelling alternative circuit arrangements to determine methods for minimizing overgrinding, and (2) determining whether new technologies, such as high-pressure roll crushing, can be used to alter particle breakage behavior to minimize fines production.

Modeling is being carried out using two variations on the “population balance” method, which solves a number of simultaneous equations to determine the size distribution of the product from the size distribution of the feed, the feedrate, and the process conditions. The models being applied use mass-balance calculations and linear algebraic methods to solve for the production of particles of each individual particle size.

Two different laboratory scale grinding machines were selected for performing this modeling:

- A Roll mill, consisting of two counter-rotating steel rollers with variable spacing, and
- A Ball mill, consisting of a cylindrical shell filled with steel grinding media.

Both mills represent equipment widely used in industrial practice. Two different types of population balance models were selected: the Matrix Model and Whiten’s Kinetic model. The model development required the determination of two main functions: Breakage or Appearance function (B for the matrix model, or A for Whiten’s model), and the Selection or Rate of appearance function (S for the matrix model, or R for Whiten’s model).

The model development phase of the project, which was funded by the Electric Power Research Institute (EPRI) used two different coal samples as the model material. The “breakage function” and “selection function” for each particle size were determined by extensive laboratory testwork. The breakage function represents the distribution of fragment sizes produced when a particle is broken, and the selection function represents the probability that a particle of any given size will undergo breakage.

The models have been implemented as Excel spreadsheets. Since this is an extremely common and well-supported format, this will make dissemination of the results of the project to industry particularly easy.

Work is currently underway to validate the model results against results from actual comminution testwork, and to determine whether there are particular benefits to applying one of the models under investigation in preference to the other.

Experimental

Models Used

The Population balance models are both systems of linear equations, and each use the same two basic functions:

- Breakage or Appearance function (B for the Matrix model or A for Whiten's model): these are square matrices which represent the product of a Breakage event, this gives the amount of particles that went to each size fraction after breakage had occurred. This function gives "how" particles from a particular size fraction are broken.
- Selection or Rate of Breakage function: (S for the Matrix model or R for Whiten's model): these are N * N matrices which give the amount of particles that were broken at a given size. This function gives "how much" particles are broken.

The difference between the models is the way in which these functions are used.

The Matrix model has the following form:

$$P = (B * S * F) + [(I – S) * F]$$

And, Whiten's model has the form:

$$P = [(I + R) – A * R)]^{-1} * F,$$

Where:

P: product size distribution resulting (a 1 * N vector).

F: feed size distribution to the grinding machine (a 1 * N vector).

B or A: Breakage or Appearance function (an N * N lower triangular matrix).

S or R: Selection or rate of breakage function (an N * N diagonal matrix).

I: Identity matrix.

N: Number of particle size intervals of interest. The sizes chosen were on a $\sqrt{2}$ series.

In order to determine the Breakage and Selection Functions it is required to experimentally determine the values for each size fraction individually for a given type of coal.

The grinding experiments were carried out using a ball mill and roll mill as well as auxiliary equipment that included: Jaw, Gyratory and Short head cone crushers. Screening into products of individual size fraction was carried out using Ro-taps and Gilson screens. Sample splitting was performed using a rotary splitter and riffle splitters.

The laboratory Ball mill used had a diameter of 205.5mm, and a length of 255mm. It included 4 rectangular lifters evenly spaced, of 17mm width and 4mm height. The ball load consisted of 123 steel balls (5000 grams) of a size between –7/8” and +1/2”. The ball mill was used because many plants still use ball mill pulverizers.

The Roll mill used was a Denver type D laboratory crushing roll, consisting of two counter rotating rolls of 6” width and 10” diameter, operating at 350 RPM. The roll mill was chosen because the action of the rolls is very similar to the pulverization action of modern industrial scale bowl-type pulverizers.

Experimental Procedure:

The work was divided into two parts. The first part focused on modeling a ball mill, and the second part was aimed at modeling the roll mill. For both it was first required to prepare suitable samples. Based on the literature review and visits to a nearby power plant it was established that the feed size to the mill should be smaller that of an inch. To achieve this, a bulk coal sample had to be crushed through several steps, which were: Jaw crusher, Gyratory crusher and Short head cone crusher. After the entire sample was crushed it was split into different size intervals. The different size intervals used are shown in Table 1.

Table 1: Size fractions used in developing the model

Mesh:	Microns
+6#	+3350
-6# .. +8#	-3350 / +2362
-8# .. +10#	-2362 / +1651
-10# .. +14#	-1651 / +1168
-14# .. +20#	- 1168 / +833
-20# .. +28#	-833 / +589
-28# .. +35#	-589 / +417
-35# .. +48#	- 417 / +295
-48# .. +65#	-295 / +208
-65# .. +100	-208 / +147
-100#	-147

This size distribution has a $\sqrt{2}$ geometrical series that is required by the model for appropriate performance. In order to produce these size fractions, the sample was first screened using a Gilson screen for coal from 6 mesh to 20 mesh. The coal that was finer than 20 mesh had to be screened using conventional Ro-Taps. When sub-samples were obtained at each size interval they were split using a rotary splitter. After this, and to assure proper classification, samples from each of the sizes were re-screened using ro-taps. This procedure had to be repeated 2 times for the Reference coal (200lb approx.) and 3 times for the Emerald coal (250lbs approx.), In order to produce enough sample for the experiments.

The procedure would vary, depending on what type of pulverizing was being studied, the procedure used for the Ball mill is the following:

- A 400 grams representative sample was taken from each size interval.
- Each sample was ground initially between 10 to 30 seconds (depending on the particle size) in order to achieve between 20% and 30% grinding. When this was accomplished, the sample was taken from the mill and screened to determine the size distribution produced. This data was used to compute the Breakage Function for that size interval.
- Once the size distribution produced has been determined, the sample was loaded again into the mill, and ground for a given time.
- The sample was again taken from the Ball mill and the amount of material remaining in the initial size determined.
- The last two steps were repeated five times. These results were used to compute the Selection Function for that size interval.

When studying the Roll mill, it was decided that there were 2 main variables that could affect the grinding performance. These variables were: Feed Rate and Roll Spacing. The effect of these 2 variables was carefully studied for the Emerald Coal. For the reference coal there was insufficient material for determining the effect of these variables, and so a fixed value of roll spacing and feed rate was used.

For the Emerald Coal, four different roll spacing were studied together with four feed rates as shown in Table 2.

Table 2: Experiments performed with the Emerald coal using the roll mill in order to study the effect of the roll spacing and feed rate in the Breakage and Selection function.

Feed Rate	**0.0 mm roll spacing**	**0.5 mm roll spacing**	**1.0 mm roll spacing**	**2.0 mm roll spacing**
Low (~60gm/min)	Experiments finished	Not necessary	Not necessary	Not necessary
Intermediate (~180gm/min)	Experiments finished	Not necessary	Not necessary	Not necessary
High (~750gm/min)	Experiments finished	Experiments finished	Experiments finished	Experiments finished
Very high (~1550gm/min)	Experiments finished	Experiments finished	Experiments finished	Experiments finished

Based on the experiments performed it was possible to include the effect of the feed rate and roll spacing for the roll mill.

It was found that the following equation could represent the changes produced when varying the feed rate and roll spacing:

$$Y = AX_1 + BX_2 + C$$

Where:

Y: Breakage or selection function value

X_1: Feed rate (gm./minute)

X_2: Roll spacing (mm.)

Results and Discussion

Based on the results obtained from the grinding experiments it was possible to prepare a spreadsheet that was able to predict the product particle size distribution based on a given feed sample.

Ball Mill: The starting point is to input the particle size distribution of the feed sample, the values had to be listed as the individual weight percent at each of the sizes included. When applying the models to the ball mill, Whiten's model has the advantage of including a scaling variable, shown as g_{calc} in the spreadsheet, based on the laboratory mill variables. In order for this to be applied the following values are required:

- Mill diameter (205.5 mm)
- Mill length (250 mm)
- Mill charge (in grams)
- The spreadsheet will calculate the charge volume based on the theoretical density of the coal being used. If the coal used has a different density it has to be input also.

Both modeling approaches are used for the Ball mill and the results are displayed as individual values and Cumulative Percent retained at each size interval used.

Roll Mill: In this case, the Reference coal and Emerald Coal models are slightly different. The reference coal had the values of the Breakage and Selection function determined for a single roll mill setting.

On the other hand, the Breakage and Selection function for the Emerald coal were calculated automatically based on the Feed rate and Roll spacing. Besides the Feed rate and Roll spacing, only the feed particle size distribution has to be input and the model will calculate the Product size distribution which will be displayed as individual a cumulative percent retained at each size.

An additional feature has also been added to this model to make it easier to apply industrial-scale mills. The roll mill used to develop this model operated at 300 rpm, and coal was fed to a 2-inch wide segment of the rolls. A full-size pulverizer will obviously not have these exact operating parameters, and so a means is needed to convert the actual pulverizer parameters into terms that can be used by the model. To do this, an additional parameter (the "roll surface loading") was determined.

The roll surface loading, L, expressed in grams/in^2, is a measure of the amount of coal being crushed by each square inch of roll surface. To calculate this parameter, the following information is needed:

- W = Roll contact width, inches. This is the width of the roll where it contacts the bowl.
- D = Roll diameter, inches
- S = Roll speed, rpm
- F = Feedrate of coal between the roll and bowl surface, grams/minute

If this information is input to the spreadsheet, it then calculates the roll surface loading, using the following formula:

$$L = F/(\pi \cdot D \cdot S \cdot W)$$

This value is used to determine an effective feedrate for the model to use to calculate the proper values for the selection and breakage functions.

Conclusions

Suitable models have been developed for predicting the grinding behavior of coal in two types of comminution machines. These models are currently undergoing validation to ensure that they accurately predict mill performance.

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