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Mining Science and Technology 19 (2009) 0097–0101

MINING
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Grinding process within vertical roller mills: experiment and simulation

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Abstract: Based on screening analysis, laser size analysis, grindability and rigidity tests of samples collected on line from a cement and a power plant, a simulation of the grinding process in vertical roller mills was carried out. The simulation calculation used a breakage function, ***B***. The results indicate that the breakage function, ***B***, and the selection function, ***S***, in the form of a matrix, can be used to express the probability of the material breaking during the grinding process. This allows the size distribution of the product to be numerically estimated. The simulation results also show that the simulated size distribution curves fit the actual experimental product curves quite well. The model provides a good starting point for simulation of the grinding process. Further research is needed to determine the proper breakage function and the matrix value of the selection function.

Keywords: vertical roller mill; grinding; simulation

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1 Introduction

Grinding is a highly energy consuming process. Considerable coal, cement raw materials and clinkers, metal and non-metal minerals, and the like, are crushed every year in China for power generation, cement manufacturing, industrial combustion and other industrial purposes. According to statistics, the energy consumption of the coal and cement grinding processes in power and cement plants accounted for 7.26% of all nationwide industrial power consumption in 2003. In 2004 grinding associated with coal-fired power plants and cement plants used 6.16% of all nationwide industrial power-consumption (see Table 1). Statistics also show that the grinding energy consumption in China was 50% higher than what would be expected at the world class, advanced level[1–2]. Therefore, optimizing grinding process parameters is a very important field of study related to energy-saving and the reduction of power consumption in China. It is estimated that power consumption could be lowered by 30%–50% after optimization of the grinding process.

Table 1 Power-consumption Statistics

	Amount of grinding (Gt)		Power consumption (10^9kWh)		Account for industrial power-consumption		Possible power-saving (10^9kWh)	
	2003	2004	2003	2004	2003	2004	2003	2004
Cement plant	0.82	1.0[3–5]	82.0	100.0	6.27	5.18	24.6–41.0	30–50
Power plant	0.826[1]	0.9[1]	17.43	18.90	1.3	0.98	5.23–8.72	5.67–9.45
Total			99.43	118.90	7.57	6.16	29.83–49.72	35.67–9.45

Note: not including other industries involving grinding.

Simulation of grinding processes started nearly a century ago. These early researchers found that the grinding processes cost huge amounts of energy. Therefore, most of their studies were aimed at energy consumption of the mills. In the meantime the modeling of the hydrocyclone used in grinding circuits was also making progress. The approach by Lynch A J was to use industrial scale experiments, which studied not only power consumption but also the entire grinding process, and to investigate other factors affecting grinding such as the type of mills, the energy costs, the property of the feed materials and the

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Received 16 July 2008; accepted 30 October 2008
Project PBK2005022 supported by the Natural Science Foundation of Jiangsu Province
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operating parameters[1–2]. Grinding process models for a ball mill were established where a selection function and a breakage function were used to describe the breaking rate and the particle size distribution. Other models that have been developed can be used to optimize production flow design, process parameters, equipment performance, raw material and operating conditions for ball mills, classifying cyclones, screen classifiers and other equipment through on-line simulations. These results were published early in the 1980's and were transformed into the commercial software JKSIMMET, which has been used in Australia, Turkey and other countries[3–4]. Current research abroad into the grinding process of ball mills, rod mills, cone crushers and autogenous mills is comparatively mature.

There have been some reports on the mathematical modeling of grinding equipment by Chinese researchers. For example: The study of general grinding dynamic equations of ultra-critical speed mills[5]; multi-factor experiments to determine the variation of grinding fineness and net energy consumption as a function of ball-mill rotation speed, grinding medium filling-ratio, feed quantity, slurry concentration and other processing variables[6]; and research on classifier overflow control systems using a new prediction control algorithm and computer simulation[7].

There are few studies both at home and abroad concerning process simulation of recently developed new equipment such as vertical roller mills and stirring mills. In China almost no work has been done on the simulation of multi-factor industrial manufacturing systems.

This paper describes the simulation of the grinding process in vertical roller mills. It is based on actual experimental data obtained on a production line at the plant and from lab experiments.

2 Experimental

2.1 Equipment

The main experimental equipment was a large-scale cement plant with a capacity of 4000 t/d. The plant is equipped with advanced technologies and has different types of grinding mills. Four grinding circuits are used with different materials: vertical mills (Loesche) for coal and cement feed; vertical roller mills for cement clinkers; and ball mills for cement products. Table 2 shows the main technical parameters of the vertical roller mill (CKP) studied in this paper.

Table 2 Main parameters of the vertical roller mill (CKP)

Capacity (t/h)	Rated power (kW)	Measured power (kW)	Roller diameter (mm)	Rotating table diameter (mm)	Rotation speed (r/min)
99	950	745	600	1 700	39.8

Sampling and experiments were also carried out in a power plant that has four ball-mill circuits used for coal grinding so that different equipment could be compared.

2.2 Sampling and experiments

All the samples used in the lab experiments were taken from the production line of the plant. The feed, intermediate materials, products of the limestone and clinker systems and the coal feed were each sampled from conveyor belts or chutes. The ground coal and final cement products were sampled with a CY40 automatic powder sampler. Each sample was taken over a period of at least two hours to ensure that a representative sample had been collected. Sampling time intervals, and the weight of the subsamples, conformed to the national and coal industry regulations and standards.

Laboratory grindability tests, screening analyses (for +0.5 mm particles), laser size analyses (for –0.5 mm particles) and comminution rate testing were carried out using the samples obtained from the three types of mills and the four grinding circuits. Sufficient reliable data was collected so that a mathematical model for a vertical roller mill could be set up. Grindability tests were completed on a non-standard ball mill. Therefore, these results are only indirectly comparable to the other data. The goal of the experiments was to optimize the grinding process, to improve comminution efficiency and to reduce energy consumption.

3 Results and discussion

3.1 Comparison of grinding results using different kinds of coals

The following data were obtained from the experiments on the coal samples from both the cement plant and the power plant (Table 3).

Table 3 Grinding results: different types of coals

Coal sample	>74 m yield (%)	Grindability factor (g/r)	Mill type	Power consumption (kWh/t)
Power plant coal	20.8	0.74	Ball mills	21
Cement plant coal	6.0	0.45	Vertical roller mills	12

The experimental results in Table 3 show that the fractions of particles sized greater than 74 μm are 20.8% and 6.0% in the screening of the power plant coal and the cement plant coal, respectively. The data indicate that the product size from the vertical roller mill in the cement plant is far smaller than that of the power plant. The grindability result is the grams of fine particles, which pass a 0.125 mm screen aperture size, produced per revolution of the mill. A standard procedure is used to determine this value. The lower the value the harder the material is. The difference in grindability between power and cement plant coal is also quite notable. Moreover, the feed coal of the cement plant is coarser than that of the power plant (Fig. 1).

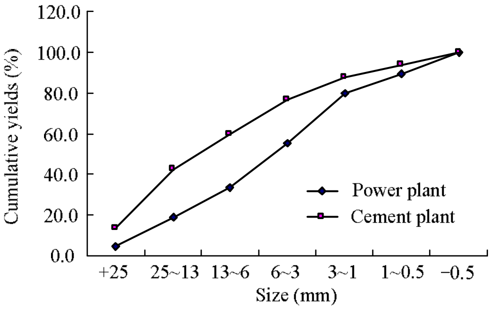

Fig. 1 Cumulative size curves of the feed coal of the two plants

The above study shows that the hardness of the coal samples taken from the cement plant is greater than the hardness of power plant coal. The feed sizes are also larger in the cement plant, compared to the power plant, but the size of the product from the vertical roller mill in the cement plant is smaller than the size of product from the power plant ball mill. It can be concluded that the process of grinding coal into fine particles for cement or power plant consumption uses less energy when grinding is done with a vertical roller mill rather than a ball mill. Obviously, this conclusion is based on the crushing process only. The energy consumption of the fans used in the classification process has not been taken into account. The example shows that optimum selection of the equipment could reduce power consumption enormously.

3.2 Analysis of the vertical roller mill

By analyzing the size distribution of the samples (Table 4) it can be seen that some improvements are needed in the performance of the cement plant equipment. The product size from the clinker mills is fine enough for the following tube mills: +6 mm accounts for only 8.3% (+13 mm/1.4%) and 97% of that is recycled by the mill’s separator. So there are only a few coarse particles in the feed material going to the ball mills. The diameter of the steel ball is much too large and much energy is wasted lifting these large diameter balls rather than grinding efficiently. Therefore, the clinker grinding rate and the overall production capacity of the ball mill circuit could be improved, without more energy consumption, by adjusting the ratio of chamber length to steel ball diameter in the following tube mills. This example shows that grinding circuit simulation can be used to analyze the production circuit, to optimize the operating parameters and to reduce energy consumption.

Table 4 Screening data of samples

Size (mm)	Clinker mill feed yield (%)	Clinker mill product yield (%)	Ball mill output yield (%)	Cyclone separation coarse yield (%)	Cyclone separation final yield (%)
25	0.8				
13	14.6	2.4			
6	16.5	5.9			
3	18.6	10.2			
1	21.2	13.9			
0.5	12.2	11.6			
(–0.5)	(16.1)				
0.25		8.2		0.9	
0.125		6.6	1.9	2	
0.074		6.5	7.1	11.6	
0.045		6.3	19.9	30.8	1.5
(–0.045)		28.4	71.1	54.7	98.5

4 Modeling a vertical roller mill

A mathematical model for the grinding process in vertical roller mills has been made. The cement plant's vertical roller mills (CKP) are used to crush cement clinkers and prepare for the next step, which are ball mills. The grinding mechanism of the CKP imposes pressure on the particles instead of impact forces. It has higher energy efficiency than do the ball mills. Although more actual operational data are required to set up an industrially practical mathematical model, the data obtained from the open-circuit vertical roller mills (CKP) are still valuable.

4.1 Breakage probability function

Observation of the size range of the input and output materials indicates that a simple breakage probability function might be a suitable starting step for setting up the model, i.e.;

$$\boldsymbol{P} = \boldsymbol{B} \bullet f \tag{1}$$

where $\boldsymbol{P}$ and $\boldsymbol{f}$ are particle size distributions of the output and input materials, respectively, and $\boldsymbol{B}$ is a breakage function.

4.2 Breakage function

The breakage function, $\boldsymbol{B}$, represents the probability that ith sized particles proceed to the size fractions from (i+1) to (i+n). The function depends on the property of the material and can be expressed as a matrix:

$$\boldsymbol{B} = \begin{bmatrix} B_{l1} & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ B_{i1} & \dots & B_{ij} & \dots & \dots \\ \dots & \dots & \dots & \dots & 0 \\ B_{n1} & \dots & B_{nj} & \dots & B_{nn} \end{bmatrix} \tag{2}$$

For vertical roller mills $\boldsymbol{B}$ is a pressure breakage function and is determined from test data. It is different from an impact force breakage function appropriate for a jaw crusher, cone crusher or ball mill. Fig. 2 shows equipment to obtain $\boldsymbol{B}$. Pressure is applied to the hammer and the sizes of the resulting particles allow a breakage function, in the form of Eq.(2), to be obtained. This is a thought experiment and, therefore, it may not fully simulate vertical roller mills. Experimental data and research experience of A J Lynch has allowed the breakage function, $\boldsymbol{B}$, for the materials in question to be established (see Table 5).

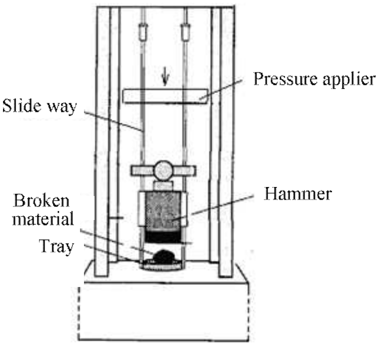

Fig. 2 Experimental set for obtaining the breakage function

Table 5 Breakage function obtained from experiments and experience

B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
0.227	0	0	0	0	0	0	0	0
0.213	0.227	0	0	0	0	0	0	0
0.180	0.213	0.227	0	0	0	0	0	0
0.146	0.180	0.213	0.227	0	0	0	0	0
0.109	0.146	0.180	0.213	0.227	0	0	0	0
0.074	0.109	0.146	0.180	0.213	0.227	0	0	0
0.046	0.074	0.109	0.146	0.180	0.213	0.227	0	0
0.031	0.046	0.074	0.109	0.146	0.180	0.213	0.227	0
0.011	0.031	0.046	0.074	0.109	0.146	0.180	0.213	0.227

4.3 Selection function

All feed particles have certain breakage probabilities. These probabilities are affected by technical conditions and will vary with particle size and the grinding stage. Call the breakage probability of size fraction i, S_i. This is the selection function, which can be expressed as a diagonal matrix:

$$\boldsymbol{S} = (S_1,\ \ldots,\ \mathrm{S}_i\ ,\ \ldots,\ \mathrm{S}_n) \tag{3}$$

The selection function, $\boldsymbol{S}$, for the materials in question has been established as:

$$\boldsymbol{S} = (0.3, 0.3, 0.3, 0.2, 0.2, \ldots, 0.2)$$

4.4 Results of simulation

Table 6 shows how the breakage function $\boldsymbol{P}=\boldsymbol{B}\bullet\boldsymbol{f}$ can be used to model the grinding process. In this example all materials are comminuted according to the breakage function, $\boldsymbol{B}$, to gain the final products.

The size of the first grinding cycle product calculated from Eq.(1) is larger than that of the experimental product. This is because the experimental materials are crushed repeatedly in the roller mill. Therefore, multiple cycles must be taken into account in the model. Suppose that the breakage probability of the second grinding cycle depends on the size of input material.

The model of the second grinding cycle can be considered as an expansion of the first one. It is expressed as:

$$\boldsymbol{P}_2 = (\boldsymbol{B}\bullet\boldsymbol{S} + \boldsymbol{I} - \boldsymbol{S})\ \boldsymbol{P}_1 \tag{4}$$

where $\boldsymbol{S}$ is the selection function.

Table 6 shows the results of calculations using this model function. The first and the second grinding cycles have the same breakage function, $\boldsymbol{B}$, because they have the same breaking mechanism. The final products are the sum of all broken and unbroken materials.

Table 6 Tabulation of actual and simulated products

Size (mm)	Actual products $\boldsymbol{P}$	Feed $\boldsymbol{F}$	Simulated products $\boldsymbol{P}_1=\boldsymbol{B}\bullet\boldsymbol{F}$	$\boldsymbol{S}\bullet\boldsymbol{P}_1$	$\boldsymbol{P}_1-\boldsymbol{S}\bullet\boldsymbol{P}_1$	$\boldsymbol{B}\bullet\boldsymbol{S}\bullet\boldsymbol{P}_1$	Simulated products $\boldsymbol{P}_2=\boldsymbol{B}\bullet\boldsymbol{S}\bullet\boldsymbol{P}_1+\boldsymbol{P}_1-\boldsymbol{S}\bullet\boldsymbol{P}_1$
13.000	2.4	15.40	3.50	1.05	2.45	0.48	2.93
6.000	5.9	16.50	7.03	2.11	4.92	1.16	6.08
3.000	10.2	18.60	10.51	3.15	7.36	1.69	9.04
1.000	13.9	21.20	13.99	2.80	11.19	1.99	13.18
0.500	11.6	12.20	11.33	2.27	9.07	2.10	11.16
0.250	8.2	1.78	9.22	1.84	7.38	2.04	9.42
0.125	6.6	1.32	7.38	1.48	5.91	1.88	7.78
0.074	6.5	2.44	5.83	1.17	4.66	1.71	6.37
0.045	6.3	2.39	5.83	1.17	4.66	2.44	7.10
–0.045	28.4	8.17	25.40	5.08	20.31	0.00	26.93
Total	100.0	100.00	100.00	27.90	72.10	18.72	100.00

Four size distribution curves are given in Fig. 3 where $\boldsymbol{F}$, $\boldsymbol{P}$, $\boldsymbol{P}_1$, and $\boldsymbol{P}_2$ represent the feed to the mills, the actual products, the first and the second grinding cycle products, respectively. $\boldsymbol{P}_2$ is also the size distribution of final products derived by calculation.

It can be seen in Fig. 3 that the two simulated product curves resemble each other and are similar to the experimental product curve. The simulated curve of the second cycle, $\boldsymbol{P}_2$, fits the actual product curve better. It indicates that the feed materials are broken more than once during the grinding process and that the working state of vertical roller mills can be simulated with a proper model. Further research is needed to reduce simulation errors and to establish more reliable breakage and selection functions.

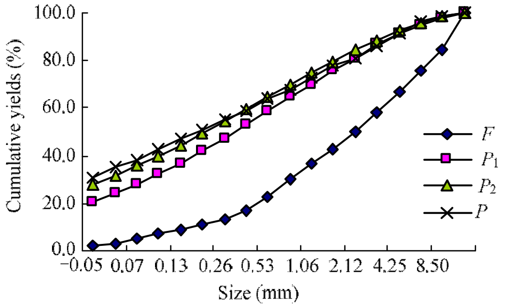

Fig. 3 Sizing curves of actual and simulated products

5 Conclusions

1) Experimental results show that the coal grinding process consumes less energy in vertical roller mills than in ball mills: it is very important to select the proper equipment to be used in the grinding process.

2) A breakage function, $\boldsymbol{B}$, and a selection function, S, in the form of a matrix, can be used to represent the breaking probability of the materials during the grinding process. This allows an estimation of the size distribution after breaking. The approach provides a good starting point for grinding simulation. Since materials typically undergo more than two breaking cycles before becoming the final product this fact should be taken into account by the model.

3) A mathematical simulation of a vertical roller mill based on experimental data has been carried out. The simulation results show that simulated size distribution curves fit the actual experimental product curves quite well. It is feasible to simulate the grinding process of vertical roller mills by using a proper mathematical model; further research is still needed.

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