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Effect of size distribution of the particulate material on the specific breakage rate of particles in dry ball milling

V.K. Gupta [1]

Department of Fuel and Mineral Engineering, Indian School of Mines, Dhanbad 826 004, India

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ABSTRACT

In the dry ball milling operation, the specific breakage rate of particles has been found to vary significantly with the size distribution of the particulate material. However, due to the lack of suitable experimental data and a clear understanding of the role of inter-particle interactions in determining the specific breakage rate of particles, it has not been possible to develop a general mathematical model that can be used to describe the variation of the specific breakage rate of particles. These limitations were overcome in our investigation by using feed charges for batch grinding experiments that were prepared according to specially designed continuous and discontinuous particle size distributions. A detailed analysis of the experimental results led to several new findings about the nature of the non-linear grinding kinetics. In particular, it was found: (i) for a given size fraction of particles, while the effect of the coarser and immediately finer sizes on its specific breakage rate was negative, the effect of the other finer sizes was positive and it increased as the particle size decreased, (ii) the overall effect varied with the material type and particle size, being more pronounced in the case of the softer material and coarse particles, (iii) the breakage distribution parameters were also significantly affected by the particle size distribution, and (iv) a simple linear relationship in terms of the mass fractions of different sizes described the variation of the specific breakage rate parameters with particle size distribution quite satisfactorily.

1. Introduction

The linear, time invariant population balance mathematical model that is generally used for describing grinding kinetics in dry ball milling operation is based on two main assumptions: (i) grinding kinetics follow a first-order law and (ii) grinding kinetics are not affected by the size distribution of the particulate material being ground, i.e. inter-particle interactions have no effect on grinding kinetics [1–7]. This model can be expressed by the following equation for the batch mode of operation [3–7]

$$\frac{dM_i(t)}{dt} = -k_i\, M_i(t) + \sum_{j=1}^{i-1} b_{i,j} k_j\, M_j(t) \tag{1}$$

where i is an index for a size interval that is bounded by the size of the openings of the upper and lower sieves, x_{i-1} and x_i, respectively; $M_i(t)$ is the mass fraction of the particulate material in the size interval i; k_j is the size-discrete specific breakage rate parameter which represents fractional rate at which particles break out of size interval j; and $b_{i,j}$ is the breakage distribution parameter, which represents the mass fraction of the product of breakage from size interval j that reports to a finer size interval i. It should be noted that the model parameters k_i and $b_{i,j}$ are not functions of M_i values, and the model is linear in the variables M_i.

During the last thirty-five years, several investigators have reported significant variations in the specific breakage rates of particles with the size distribution of the particulate material being ground [8–15]. Austin and Bagga [8] were the first to report that in the case of two types of cement clinkers and two types of coals the specific rates of breakage of all sizes slowed down significantly when the amount of fines exceeded a certain limit in individual cases. The slowing down of the breakage rates was attributed to the cushioning action of fines. This was followed by a study carried out by Gupta [9] in which the effect of the size distribution of the particulate charge on the specific breakage rate of the top size fraction was studied. The feeds for grinding experiments were prepared by mixing 14/20 mesh (1180/850 μm) coarse fraction and −20 mesh (−850 μm) fine fraction of a specific size distribution in various proportions. Limestone and quartz were used as the test materials. It was found that as the amount of 14/20 mesh size fraction in the feed was reduced from 89 to 9%, the specific breakage rate of this size fraction increased by about 35% in the case of limestone and by 27% in the case of quartz. A similar investigation was carried out by Verma and Rajamani [10]. They prepared two feeds of limestone with different size distributions. The fine feed had a natural size distribution with approximately 17% material in the 10/14 mesh (1700/1180 μm) top size

E-mail address: gupta.vinaig@gmail.com.
[1] Present address: B-402 Bansal Plaza, Station Road, Ranchi 834 001, India.

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interval, and the coarse feed had 31% material in the top size interval. Their results show that the initial specific breakage rate of the 10/14 mesh particles was approximately 60% higher in the case of the finer feed. In contrast with these two studies [9,10], Gupta [11], Celik [12], Fuerstenau and Abouzeid [13] and Fuerstenau et al. [14] used feeds with discontinuous size distributions. Gupta [11] presented results of an experimental study in which the size distribution of the feed charge was varied in several different ways by removing a particular size fraction and adding an equivalent amount of one or more of the finer size fractions. The mass fraction of the top size fraction in the feed charge was kept constant. It was found that the finer the replacement material, the greater was the increase in the specific breakage rate of the top size fraction. Moreover, as compared with quartz, this effect was found to be more pronounced in the case of limestone. Celik [12] dry ground 20/30 mesh (850/600 μm) size fraction of anthracite alone and also as a 50–50 mixture of 20/30 mesh size fraction and −200 mesh (−75 μm) anthracite powder to study the effect of fines on the specific breakage rate of the top size fraction. A 60% increase in the specific breakage rate of 20/30 mesh size fraction was observed when it was ground as a mixture. Fuerstenau and Abouzeid [13] and Fuerstenau et al. [14,15] also studied the effect of fines on the comminution behaviour of coarse material for quartz, dolomite and limestone. Two sets of feeds were prepared for grinding experiments by mixing 10/14 size fraction (1700/1180 μm) with −48 mesh (−300 μm) and −100 mesh (−150 μm) size fractions in various proportions. Their results of the grinding experiments show that as the proportion of 10/14 mesh size fraction in the feed was reduced from 100 to 15%, the specific breakage rate of this size fraction increased by 76, 108 and 145% in the case of quartz, dolomite and limestone, respectively. Further, it was found that the increase in the specific breakage rate of 10/14 mesh size fraction was less in the presence of −48 mesh material as compared with the increase observed in the presence of −100 mesh material (53 vs. 76% in the case of quartz, and 100 vs. 145% in the case of limestone).

The scope of the investigations discussed above is found to be limited to finding out the overall effect of fine material characterized by a single parameter such as the weight percent finer than 100 mesh (−150 μm). However, for the development of a general relationship, the effect of individual sizes on the specific breakage rate of particles of other sizes should be known. Therefore, in our investigation the required information was generated by analyzing the results of a large number of specially designed grinding experiments. This information was used to develop the desired mathematical relationship for describing the variation of the specific breakage rate of particles with the size distribution of the particulate material in dry ball milling. Several other important basic facts about the nature of the non-linear grinding kinetics could also be established.

We would like to mention that in our study we have limited ourselves to a size distribution regime in which the proportion of −400 mesh (−38 μm) material does not exceed 50%.

2. Background and approach

The first indications of the effect of particle size distribution environment on the specific breakage rates of particles came from the results of batch grinding tests performed with the leftover material after completing the study on the effect of ball and mill diameters on the specific breakage rate of particles in the year 1984 [16]. The leftover material was deficient in the coarser sizes and, therefore, feed charges prepared with this material were significantly finer than the single-size feeds used in the earlier work. It was found that the specific breakage rate values obtained from these tests were higher than those predicted by the correlations given in [16].

After some time, we got a strong indication from the results of a duplicate test that was planned to check the reproducibility of results. In this test, during the preparation of the feed charge, due to an oversight, instead of adding the desired quantity of material from the bag containing a premixed 28/65 mesh (600/212 μm) material, an equal amount of material from the bag containing −200 mesh (−75 μm) material was added. The mistake was discovered when it was found that the value of the specific breakage rate of the 20/28 mesh (850/600 μm) top size fraction was nearly twice the value obtained in the previous test. With a view to developing a better understanding of the effect of particle size distribution, a large number of tests were carried out by varying the size distribution of the feed charge in several different ways. Results of some of these tests are given in Tables 1 and 2. It can be seen that in general the effect of the size distribution of the particulate material on the specific breakage rate of the top size fraction is quite significant.

In another series of tests, 14/35 mesh (1180/425 μm) and −35 mesh (−425 μm) size fractions of quartz and limestone were mixed in ratios of 3:1 and 1:3 to obtain a coarse and a fine feed charge of each material. These were batch ground for the same length of time which corresponded to about 50% reduction of the top size. The product size distribution data obtained for the finer charge was used to predict the size distribution of the coarser one, based on the linear kinetics assumption. The following relationship

$$R_i(coarse) = 3 \times R_i(fine) \quad (2)$$

where R_i denotes cumulative mass fraction retained on the lower sieve of size interval i, was expected to hold good for at least the top two sizes: 20 mesh (850 μm) and 28 mesh (600 μm). A comparison of the actual and predicted R_i values given in Table 3 will show that there is a significant departure from linear kinetics, differences being more pronounced in the case of limestone.

After carrying out the preliminary experiments described above, additional batch grinding experiments were carried out using a more systematic approach to varying the size distribution of the particulate charge. This approach involved removing a particular size fraction and adding an equivalent amount of one or more of the finer size fractions, while keeping the amount of material in the top size interval constant (see Tables 4–7). For the first set of experiments, 14/20 mesh (1180/850 μm) was chosen as the top size. Four other size classes were defined by combining two or more sieve size intervals as follows: 20/35 mesh (850/425 μm), 35/100 mesh (425/150 μm), 100/400 mesh (150/38 μm) and −400 mesh (−38 μm). For a special purpose, a deviation from this design was made in the case of a set of three experiments shown in Table 6. Limiting the total number of size classes to only five was considered necessary for convenience in the design of experiments and carrying out the analysis of the experimental data. For the second set of experiments, 100/150 mesh (150/106 μm) was chosen as the top size. In this case, as the total number of basic size classes happened to be five (see Table 7), it was not required to combine two or more sieve size intervals.

Table 1
Variation of the specific breakage rate of the 20/28 mesh (850/600 μm) size fraction of quartz with the mill charge particle size distribution in the 29 × 18 cm ball mill.

Size interval, mesh	Weight % in the size interval		
	Test no.		
	1	2	3
20/28	47.4	14.8	15.0
28/35	12.9	13.9	2.0
35/48	13.6	17.0	0.0
48/65	9.2	15.3	1.2
65/100	6.5	13.3	6.0
100/150	3.7	7.9	10.3
150/200	3.0	7.2	15.3
−200	3.7	10.6	50.2
$k_{20/28}$, min^{-1}	0.23	0.28	0.47