Grinding Behavior of Coal Blends in a Standard Ball-and-Race Mill

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An investigation was carried out to predict the size–composition make-up of the product of a coal blend ground in a ball-and-race mill using the breakage characteristics of the individual components determined by separate grinding. Sometimes a pseudolinearity can be observed when the changes in the grinding rate for the components in the mixture occur in a compensated manner. In this case, the HGI of the blend appears to be additive. However, the composition of the product size intervals is different from the weighted sum of the two products from separate grinding. An empirical equation was used to predict the change in the breakage parameters as a function of the blending ratio and the difference between the relative strength of the two materials. The grinding of the individual coals in the Hardgrove mill exhibited non-first-order grinding kinetics. Consequently, the false time concept for fines accumulation was used to predict the grinding behavior of the coal blends with reasonable accuracy. The locked-cycle simulation for grinding a binary mixture shows that the content of the mill charge becomes richer in the stronger component. The system attains steady state when the absolute production rates of both materials are the same, although the ratio of materials in the mill charge is not necessarily the same as the ratio in the feed. As a result, the production rate can be lower than expected based on the ratio of the feed.

Introduction

Coal blending serves the purpose of controlling coal bulk characteristics to meet some specifications and/or emission standards in existing power plants. However, the grindability, as measured by the Hardgrove Grindability Index (HGI), of the blend is of great interest since it predicts the capacity of the pulverizers. As a consequence, there have been numerous investigations[1–5] of the HGI's of blends with special interest in the additivity of the HGI. Some coal blends show additivity of HGI, but generally this is not the case. Thus, there is no general method for predicting the HGI of a coal blend, and, hence, it must be determined experimentally case by case. This, in turn, makes it very difficult to set the grindability specification of the coals to be blended.

In addition, determining the HGI of a coal blend alone does not give sufficient information needed for proper combustion because the combustion engineer needs to know the size distribution and the composition of the ground product. When grinding mixtures of materials with different strengths, it is conceivable that the weaker component concentrates in the finer fractions. If the product is considered as the material below a certain size, then the proportion of the weak component will be higher than the feed. Also, when the material above the size is recycled back to the mill (closed-circuit grinding), the mill charge contains a greater proportion of the stronger component than the feed due to the buildup of the stronger component in the mill via recirculation. In this case, the overall HGI value can give false information on the performance of a closed circuit grinding system since the composition of the mill content is different from the feed. Therefore, it is necessary to predict the grinding behavior of the individual components in blends to make the right product with the desired size distribution and composition. This is only possible by the analysis of the grinding behavior of the components in a blend during simultaneous grinding in terms of the kinetic grinding model.[6]

The kinetic grinding model has been successfully used for predicting the outcome of various grinding systems. Unfortunately though, the breakage characteristics of a component change when ground with another material.[7,8] Therefore, the breakage parameters for a material must be determined separately for a given blend in order to produce satisfactory predictions. Experimental determination for each case is tedious and often impossible due to the difficulty in measuring the individual grinding behavior of components in blends. Rather, it is more desirable if the variation of the breakage parameters during the grinding of a blend is predicted

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(5) Douglas, R. E.; Mai, M. C. Effects of Increasing Coal Hardness and Volatility on Pilot-Scale Pulverization and Combustion Performance. *Proc. Seventh Int. Pittsburgh Coal Conf., Pittsburgh,* **1990**, 837–851.
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(7) Fuerstenau, D. W., Abouzeid, A. M., Venkataraman, K. S.; Deason, D. M. Grinding of Mixtures of Minerals: Kinetics and Energy Distribution. *Proc. 1. World Congr. Particle Technol., Part II. Comminution, Nuremberg* **1986**, 415–426.
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Table 1. Analysis of Coal Samples

	Coal A	Coal B	Coal C	Coal D
% moisture	7.1	5.2	0.8	1.2
% ash	15.7	12.4	28.3 (7.1[a])	23.1 (7.4[a])
% volatile	19.8	30.6	21.0	29.0
% fixed carbon	64.5	57.0	50.8	48.0
HGI	83	55	72	50

[a] 1.5 float fraction.

from the information gleaned in grinding individual components.

In a previous study,[9] a quantitative description of the change in the breakage parameters was determined as a function of the blending ratio and the relative difference in the "strength" of the two components. This change is given by

$$a_m = a\left(\frac{1-F}{0.1}\right)^E, \quad F \geq 0.1$$
$$= a, \quad F < 0.1 \tag{1}$$

where a_m is the specific rate of breakage of a component of size x_0 in a binary mixture, a is the specific rate of breakage of the component of size x_0 when ground separately, and F is the volume fraction of the component in the mixture. E is the variable representing the difference in the breakage rates given by

$$E = \log\left(\frac{a_A - a_B}{a_A + a_B}/0.09\right)^C, \quad \frac{a_A - a_B}{a_A + a_B} \geq 0.09$$
$$= 0, \quad \frac{a_A - a_B}{a_A + a_B} < 0.09 \tag{2}$$

where a_A and a_B are the breakage rates of the weaker component and the stronger component, respectively, of size x_0, when ground separately. The C values determined by regression are -1.16 for the stronger components and 0.49 for the weaker components.

Also, it was found that the breakage distribution values of the stronger material were independent of whether it was ground alone or as a component in a binary mixture. However, the values of the weaker material varied in a systematic manner where more fines are produced when ground in the presence of larger amounts of the stronger material. It is the purpose of this study to use these relationships to predict the size and composition make-up of the ground product of binary coal blends and analyze a simple case of a closed-circuit system with a mixture feed.

Experimental Section

The analyses of four high volatile bituminous coals used in this study are given in Table 1. Since coal C and coal D have a higher ash content, their samples were floated at 1.5 specific gravity using Certigrav solution to reduce the heterogeneity thereby changing the blend from a trinary to a binary blend (a prime will be used to denote the 1.5 float samples of these coals). The batch ball-race mill tests were conducted in a standard Hardgrove machine. The grinding procedure of the standard Hardgrove grindability test was followed, except that narrowly sized materials were used. A mixture was prepared on a weight basis rather than a volume basis because the relative densities of the four coals did not differ from each other. For each test, a 50 g sample (single or mixture) was ground for various times at the rotation speed of 20 rpm and with a force of 64 lb. A fresh sample was used for each grinding period. The ground material was sieved to obtain a size distribution.

(9) Cho, H.; Luckie, P. T. Investigation of the Breakage Properties of Components in Mixtures Ground in a Batch Ball-and-Race Mill *Energy Fuels* **1995**, *9*, 53–58 (preceding paper).

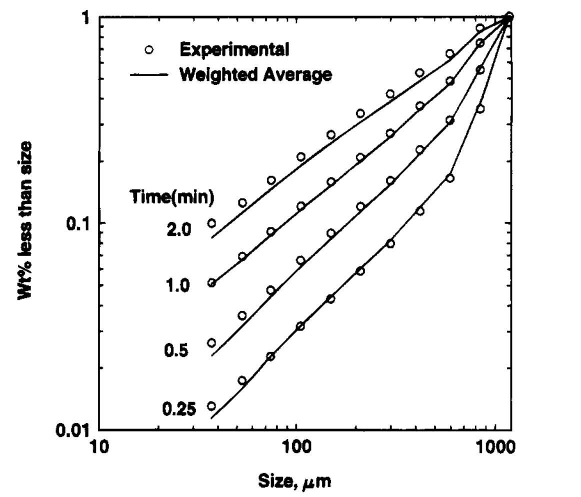

Figure 1. Comparison of the experimental and the weighted average size distributions for grinding 16 × 20 mesh coal A–coal B 50/50 mixture.

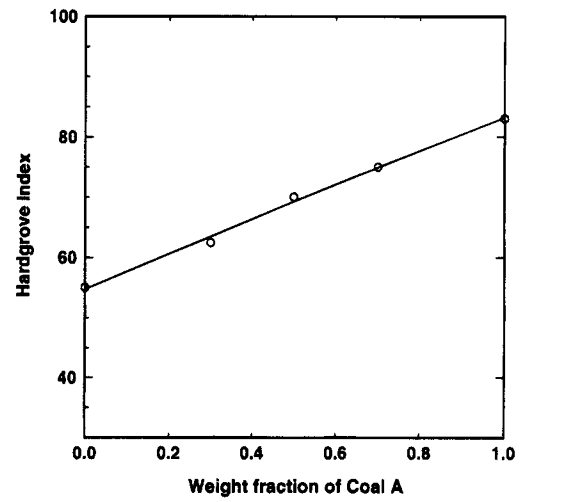

Figure 2. Hardgrove Indices for coal A–coal B mixtures as a function of mixture composition.

Results and Discussion

Figure 1 shows the size distribution for the grinding of a 50/50 blend of coal A and coal B compared with the simple weighted average of the two size distributions for coal A and coal B from separate grinding. Excellent agreement exists between the two sets of size distribution for all blends. A similar trend was observed for the 30/70 and 70/30 blends. Likewise, a linear relationship exists between the Hardgrove Grindability Indices of the blends, determined by blending the 16 × 30 mesh samples, and the blending ratio, as shown in Figure 2. However, this does not necessarily mean that the grinding system is linear, but only that it appears to behave linearly, since there are many combinations of two size distributions which will produce the same size distribution. In other words, the ratio of coal A to coal B in the size fractions might be different even though the size distribution is the same. Thus, the most that can be concluded is that the system behaves in a

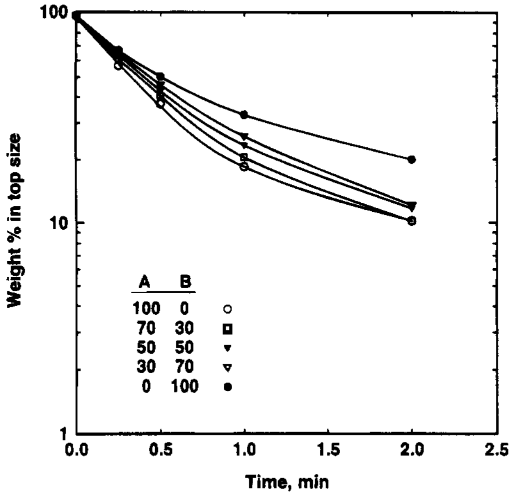

Figure 3. First-order plots for mixtures of 16 × 20 mesh fractions of coal A and coal B.

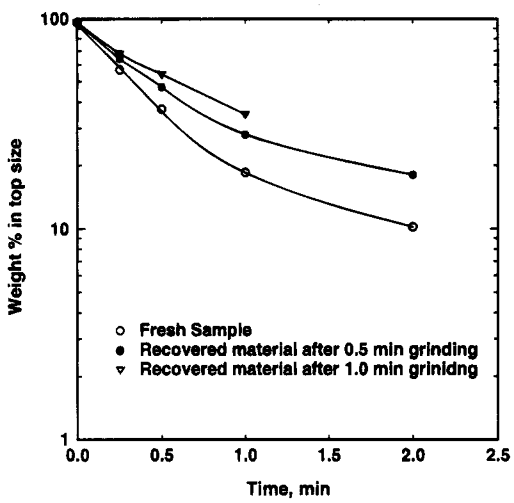

Figure 4. First-order plots for 16 × 20 mesh fractions of coal A recovered after some time of grinding.

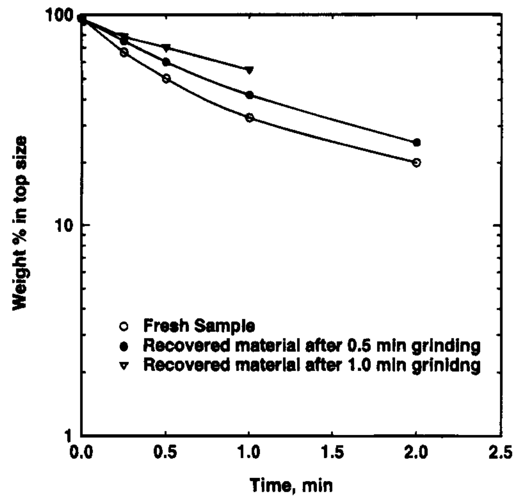

Figure 5. First-order plots for 16 × 20 mesh fractions of coal B recovered after some time of grinding

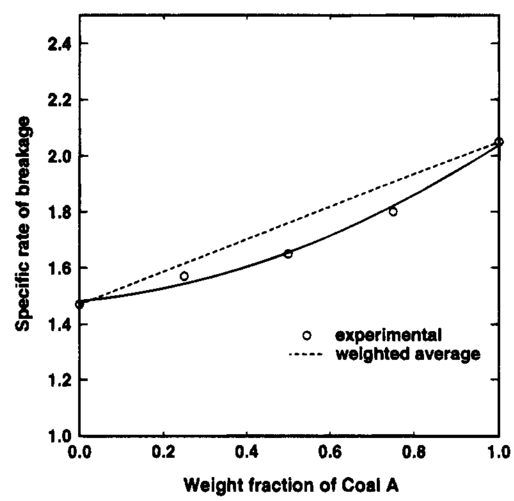

Figure 6. Variation of the breakage rates for mixtures of coal A and coal B with mixture composition.

pseudolinear fashion. A similar case was reported by Kanda et al.[10] in a grinding study of quartz and limestone 50/50 mixtures. It was found that the overall rate of simultaneous grinding was almost equal to the average rate for the mixture from the separate grinding rate of each component, even though the grinding rate of each component changed when ground together.

Figure 3 shows the overall disappearance plot of coal A and coal B and blends of the two at the three different blending ratios. The breakage rate of each blend lies between the breakage rate of the two coals for separate grinding, an expected pattern. Unfortunately, the breakage rates exhibit non-first order behavior at longer grinding times. Non-first order behavior is expected for a blend because the different grinding properties of the single coals cause the blend to grind as a binary mixture of strong and weak components. However, the reason for the single coal behavior is not obvious. A coal grinding study in a Hardgrove machine by Austin et al.[11] showed that the deceleration of the breakage rate was due to the accumulation of fine particles. However, for coals with high ash content (above 10%), it was observed that the variation of the grinding properties between the organic and inorganic components of the coal caused them to grind as a binary mixture of strong and weak components.[12]

In order to determine the cause for the slowing down of the breakage rates of the two coals, a separate test was conducted. A 50 g sample of 16 × 20 mesh material was ground for a specified time. The material was then sieved and the 16 × 20 mesh material recovered. This procedure was repeated until enough 16 × 20 mesh material was collected for separate grinding tests. A series of grinding tests to determine the specific rate of breakage was then conducted using the recovered 16 × 20 mesh material.

Results are shown in Figures 4 and 5 for the 16 × 20 mesh material recovered after 0.5 and 1.0 min. It can be seen that the initial breakage rates of the recovered material are lower than that of the fresh material. Also, it can be seen that the breakage rate of the material collected after 1 min decreases further, indicating that the stronger material remains in the feed size as the grinding proceeds. The ash contents of the material recovered after 1 min of grinding were 22.3 and 36.4

(10) Kanda, Y.; Abe, Y.; Sasaki, H. An Examination of Ultra-fine Grinding by Preferential Grinding *Powder Technol.* **1988**, *56*, 49–53.
(11) Austin, L. G.; Shah, J.; Wang, J.; Gallagher, E.; Luckie, P. T. An Analysis of Ball-and Race Milling, Part I. The Hardgrove Mill *Powder Technol.* **1981**, *29*, 263–275.
(12) Lytle, J. M.; Prisbrey, K. A. Material-Dependent Non-Linear Modeling of Fine Coal Grinding. *Powder Technol* **1984**, *38*, 93–97.

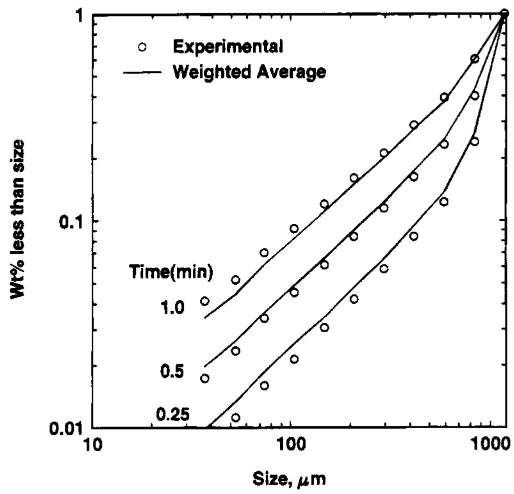

Figure 7. Comparison of the experimental and the weighted average size distributions for grinding 16 × 20 mesh coal C′–coal D′ 50/50 mixture.

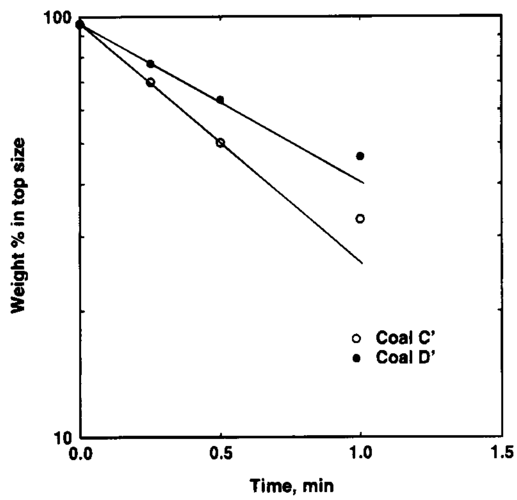

Figure 8. First-order plots for 16 × 20 mesh fractions of coal C′ and coal D′.

wt %, respectively, compared to 13.8 and 17.4 wt % for the original 16 × 20 mesh materials. From these results, it can be concluded that the heterogeneous nature of the coals is partly responsible for the slowing down of their breakage rates. The accumulation of fines also causes a slowing down of the breakage rate for these coals, since the breakage rates at 1.0 min with fines are much lower than those of the material without fines.

Figure 6 shows the plot of the initial breakage rate against the amount of coal A in the blend. It can be seen that the overall breakage rate of the mixture is lower than the weighted average values. As shown by Venkataraman,[13] at short grinding times, the breakage rate of a mixture is approximately equal to the weighted average of the breakage rate of the components if the breakage rates do not change. Therefore, it can be concluded that the breakage rate of the components varied in such a way as to yield a decrease in the overall breakage rate for the mixture.

Figure 7 shows the similar comparison for the 50/50 blend of coal C′ and coal D′. It can be seen that the experimental size distribution does not agree with the weighted average of the two size distributions. This indicates that grinding of the blend is not linear and thus the breakage properties definitely change when ground with another material. Specially for this blend, the changes in the breakage properties of the components did not occur in a compensating manner to give a pseudolinear result.

(13) Venkataraman, K. S. Specific Energy Consideration in Mixture Grinding. M.S. Thesis, University of California, Berkeley, 1981.

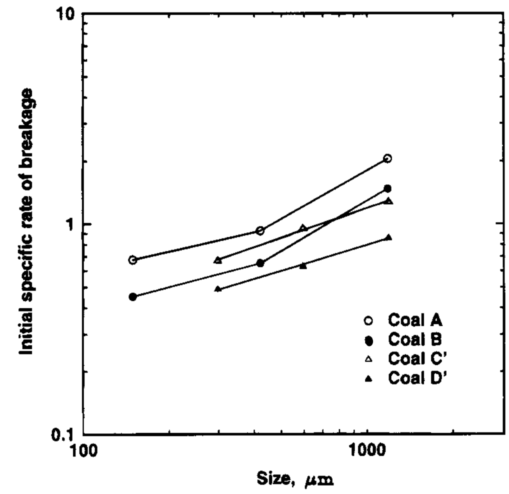

Figure 9. Initial specific rates of breakage as a function of size for four coals.

Figure 8 shows the breakage rate for the 16 × 20 mesh samples of coal C′ and coal D′. It can be seen that the breakage rates are initially first order but show some non-first-order behavior at longer grinding times. It can be assumed that the slowing down of breakage rates was mainly due to the accumulation of fines because the ash content of these coal samples after floating them at 1.5 specific gravity is less than 10%.

Application of the Empirical Breakage Parameter Relationship to Blends of Coals. The size distribution of the grinding product at any time t can be easily obtained from the solution to the well-known batch grinding equation

$$\frac{\mathrm{d}w_i(t)}{\mathrm{d}t} = -S_i w_i(t) + \sum_{j=1}^{i-1} b_{ij} S_j w_j(t) \qquad (3)$$

where S_j is the specific breakage rate of material in the jth size interval and b_{ij} is the fraction of material broken out of the larger jth size interval appearing in the ith size interval. The grinding of blends cannot be simulated by using the breakage rate and breakage distribution values for the mixture, i.e., treating the blend as if it were a homogeneous material, due to the non-first order breakage rate caused by the build up of the stronger component. A more accurate and simpler way to simulate the grinding behavior of blends is to apply the batch equation separately for each component with its own breakage rate and the breakage distribution values. The overall product size distributions of a mixture then can be calculated as the weighted sum of the individual size distributions according to the fractional amount of each present

$$w_i(t) = \Phi w_{Ai}(t) + (1 - \Phi) w_{Bi}(t) \qquad (4)$$

where Φ is the weight proportion of the material A in the mixture: $w_{Ai}(t)$ and $w_{Bi}(t)$ are the weight fraction of

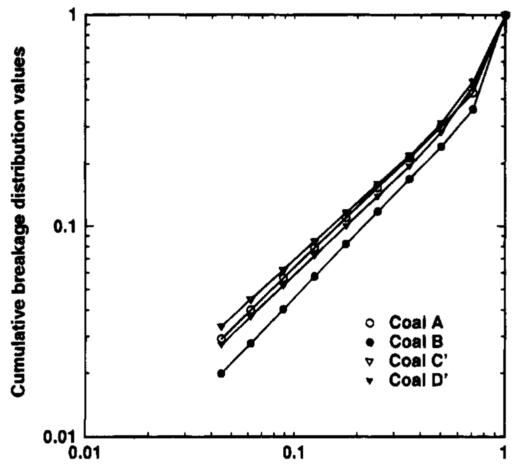

Figure 10. Cumulative primary breakage distribution for four coals.

Table 2. Breakage Parameters for the Coal Samples

	a	α	ϕ	γ	β
coal A	2.05	0.3	0.58	0.96	10.0
coal B	1.47	0.35	0.49	1.03	10.0
coal C′	1.27	0.5	0.55	0.90	5.0
coal D′	0.850	0.55	0.51	0.94	5.0

materials A and B, respectively, in the ith size class at time t that can be calculated from eq 3.

Figure 9 shows the values of the breakage rate for all four coal samples as a function of size, determined from the initial slope of the disappearance plots. For coal C′ and coal D′, the trend shows a typical power function relationship

$$S_i = a(x_i/x_0)^{\alpha} \tag{5}$$

where S_i is the specific rate of the particle size x_i. However, for coal A and coal B, a break in the values can be seen, similar to the results obtained in the study by Austin et al.[11]

Figure 10 shows the cumulative breakage distribution for the four coal samples. It is seen that the calculated values follow a general trend of the weaker coals producing more fines. The cumulative breakage distribution values, denoted by B_{i1}, are the cumulative weight fraction of material broken from size 1 which appears smaller than the upper size of size interval i. These values can be fitted by the empirical function

$$B_{i1} = \phi\left(\frac{x_{i-1}}{x_1}\right)^{\gamma} + (1-\phi)\left(\frac{x_{i-1}}{x_1}\right)^{\beta} \tag{6}$$

Table 2 gives the descriptive parameters for eq 5 and 6.

The breakage rate of each coal in the blend was calculated using eqs 1 and 2. In eq 1, the increasing and decreasing factors for the a values were estimated as follows: for coal A, 1.15, 1.23, and 1.28 and for coal B, 0.55, 0.61, and 0.72 for 70/30, 50/50, and 30/70 blending ratios, respectively. Unfortunately, the estimation of the a values is not sufficient, since these two materials exhibited a slowing down of the disappearance rate due to heterogeneity and the accumulation of fines.

The simulation was performed only up to 1 min, where heterogeneity should be insignificant, using the false time concept[14] to handle the accumulation of fines. The false time, θ, is the equivalent first-order grinding time. In other words, if the breakage rate remains first order, the size distribution at time t would be equivalent to the size distribution at time θ. Here, the slowing down of the breakage rate is assumed to be uniform for all sizes. Then, the breakage rate at time t can be represented by

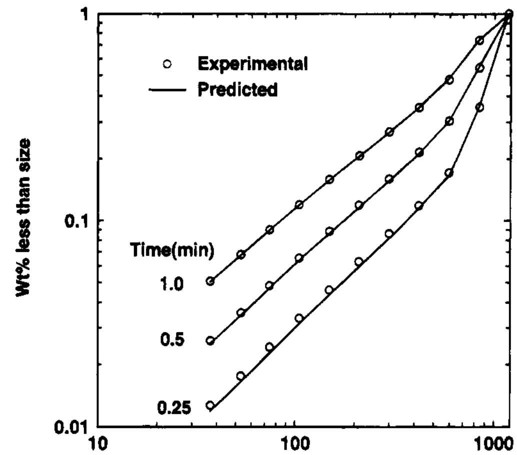

Figure 11. Comparison of the experimental and the computed size distributions for grinding 16 × 20 mesh coal A–coal B 50/50 mixture.

Table 3. Estimated θ Values for Grinding Blends of Coal A and Coal B

	blending ratios					
	30/70		50/50		70/30	
time, min	coal A	coal B	coal A	coal B	coal A	coal B
0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.50	0.50	0.50	0.50	0.50	0.50	0.50
1.00	0.95	1.00	0.95	0.95	0.95	0.95

$$S_i(t) = KS_i(0) \tag{7}$$

where $S_i(0)$ is the initial breakage rate and K is a reduction factor. The slowing-down factor K is related to θ and t by

$$K = \theta/t \tag{8}$$

As the grinding proceeds, K decreases as more fines build up in the charge. False times were determined separately for each coal because the breakage rate of each slowed down at a different rate. Table 3 lists the θ values for each coal at various blending ratios.

Simulations were performed without changing the breakage distribution values of either component. The results are shown in Figures 11–13. It can be seen that the simulated results are in reasonable agreement with the experimental results for the 70/30 and 50/50 blends. However, for the 30/70 blend, the simulated results are slightly coarser than the experimental. This indicates that the breakage distribution values of one of the components have changed. In a previous study,[9] it was observed that only the ϕ breakage parameter of the weaker component changed with the value for the 30/70 mixture increasing by 0.15. Therefore, simulations were conducted with a ϕ value of 0.70 for coal A. The

(14) Austin, L G.; Bagga, P. An Analysis of Fine Dry Grinding Ball Mills. *Powder Technol.* **1981**, *28*, 83–90.

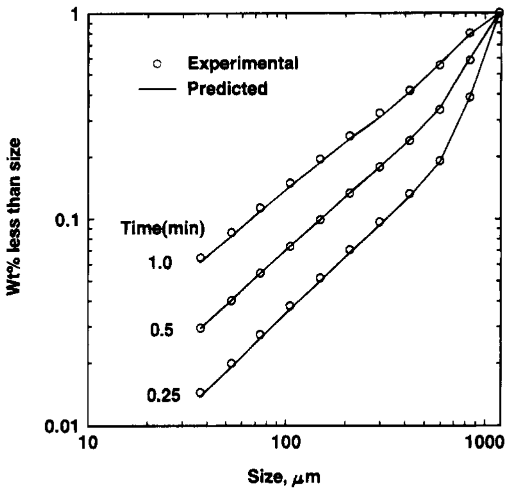

Figure 12. Comparison of the experimental and the computed size distributions for grinding 16 × 20 mesh coal A–coal B 70/30 mixture.

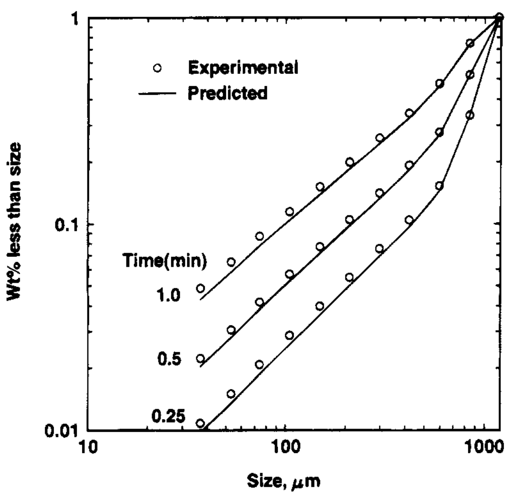

Figure 13. Comparison of the experimental and the computed size distributions for grinding 16 × 20 mesh coal A–coal B 30/70 mixture.

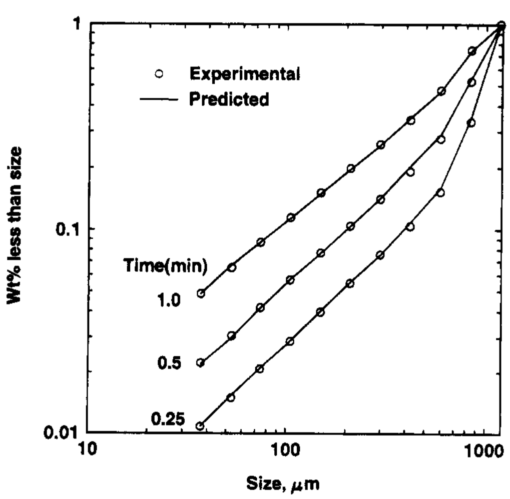

Figure 14. Comparison of the experimental and the computed size distributions with a higher ϕ value for coal A for grinding 16 × 20 mesh coal A–coal B 30/70 mixture.

results are shown in Figure 14, where a better agreement between the simulated and the experimental values can be seen.

Figure 15a compares the size distributions of the products of blends of coal A and coal B prepared in two

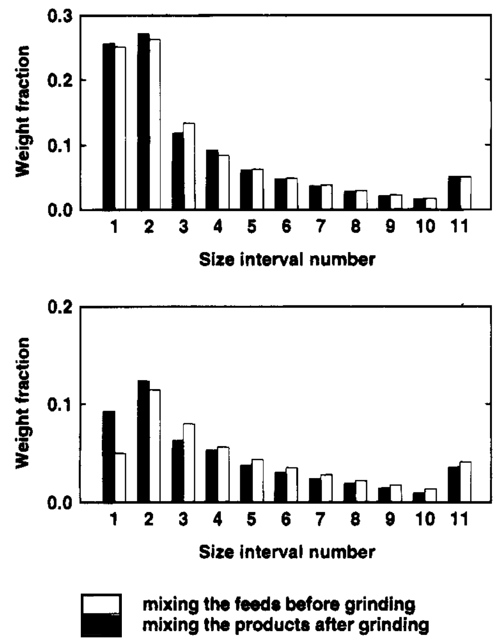

Figure 15. Comparison of the products of coal A–coal B mixtures prepared by two ways: (1) 1:1 mixing of the feeds before grinding and (2) 1:1 mixing of the products after grinding; (a) overall size distribution, (b) weight fraction of coal A in each size interval.

ways; (1) 1:1 mixing of the feeds before grinding and (2) 1:1 mixing of the products after grinding. For both cases, the grinding time was 1.0 min. It can be seen that the product size distributions are almost the same. However, as seen in Figure 15b, the composition of the various size fractions is different, since the grinding rate of each component changes when ground together. In fact, the fraction of coal A is about 20% higher for the finer size fractions for the case of mixing the feeds before grinding, due to the increase in the breakage rate of coal A. This is a case of pseudolinearity, which can be observed when the increase in the grinding rate of one component is exactly compensated for by the decrease in the grinding rate of the other component.

As discussed previously, this was not the case for blends of coal C′ and coal D′. To predict the size distributions for 50/50 blend of coal C′ and coal D′, eqs 1 and 2 were again used. The computed a values were 1.66 and 0.45 min^{-1}, respectively. Since these two coals also exhibited deceleration of the breakage rate after 0.5 min of grinding, it was necessary to estimate the false time for the 1 min of grinding time (0.9 min for both coals). Figure 16 shows the comparison of the computed and the experimental size distributions. It can be seen that the simulated results are in good agreement with the experimental.

Analysis of a Closed-Circuit Grinding System with a Mixture Feed. During the closed circuit grinding of mixtures, the composition of the mill contents may be different from the feed, since the stronger component can build up in the mill as more of the stronger component in the coarser sizes is recycled via the classifier to the mill. Since the breakage rate of the components changes with the variation in the composition of the mill charge, depending on the relative grindability of the individual components, it is necessary to know the composition of the mill content of a closed circuit grinding system at steady state. Unfortunately,

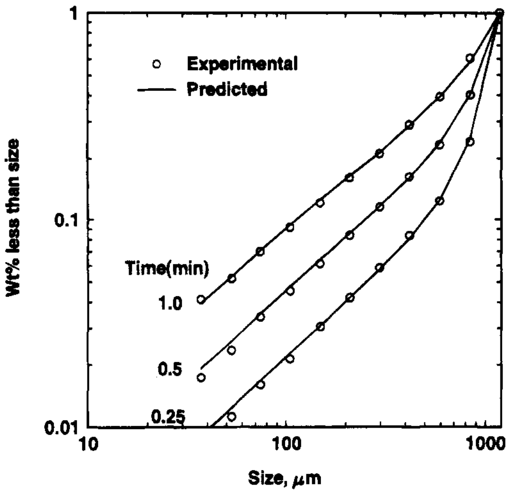

Figure 16. Comparison of the experimental and the computed size distributions for grinding 16 × 20 mesh coal C′−coal D′ 50/50 mixture.

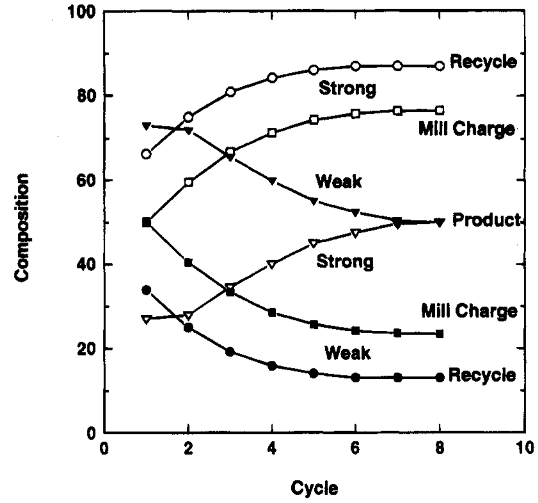

Figure 17. Variation of composition of recycle and product with the grinding cycle.

this cannot be precalculated since the result is an outcome of the contribution of many variables including the feed size distribution, the feed composition, the relative grindability of the individual components, the classifier efficiency and the feed rate.

Closed-circuit steady-state grinding can be easily emulated by conducting locked-cycle grinding tests, the repetitive application of the batch procedure followed by sieving. Since two components are being ground simultaneously, it is necessary to simulate the locked-cycle testing in order to trace how much of each component is recycled to the mill and then calculate the composition in the mill to change the breakage kinetics parameters of the components appropriately.

For example, consider the simulation of locked-cycle grinding of a 1:1 mixture of Lower Freeport seam coal and Ohio No. 9 seam coal. The breakage parameters chosen for these two coals were reported by Austin et al.[11] The feed size distributions of the two coals were arbitrarily chosen but with the weaker coal having the finer size distribution. The locked-cycle simulations were conducted with a sieve size of 75 μm and a grinding time of 2.5 min. After each cycle of simulation, the amount and the size distribution of the material on the sieve were calculated for each component. Then, the size distribution of the mill content for the next cycle was calculated from the weighted sum of the size distributions of the oversize and the fresh feed. The fresh feed was always taken in the ratio of 1:1. Since the mill content is changing, the breakage rates of the components were adjusted at each cycle according to eqs 1 and 2. This procedure was repeated until the production rate became constant.

Figure 17 shows the composition of the sieve oversize (recycle) and the undersize (product) as a function of the cycle number. It can be seen that the content of the stronger coal in the product increases as the cycle proceeds, eventually reaching 50%. It is also seen that the content of the stronger coal in the recycle increases to make the mill charge increasingly richer in the stronger coal. Thus, the production rate of the stronger coal increases as the lower breakage rate of the stronger coal is compensated by the larger quantity. The system eventually attains steady state when the absolute production rates for both coals are the same. As expected, the proportion of the stronger coal in the mill charge at steady state is higher than in the feed, 76.5 versus 50%.

However, the composition of the mill charge at steady state varies with the grinding time employed. As the grinding time increases, the production of the undersize material for the stronger coal increases relatively more than for the weaker coal and, in turn, the system attains a steady state with a lower content of the stronger component in the mill charge. In an actual closed-circuit grinding of a mixture, the situation is even more complicated. Because of the incomplete classification, the recycle can have a higher proportion of the weaker component, producing a higher content of the weaker component in the mill holdup. This can be easily incorporated into the simulation with an accurate description of the classification behavior with respect to particle size.

In general, overall HGI determined by the feed composition can overestimate the capacity for a pulverizer for a closed-circuit grinding system since it does not account for the buildup of the strong component in the mill charge. Priori knowledge of the mill charge composition is needed to better predict the mill capacity by HGI based on such a mill composition. This can be obtained by simulation such as the locked-cycle simulation.

Conclusions

The grinding of binary coal blends in a Hardgrove mill is not linear. However, sometimes a pseudolinearity can be observed when the increase in the grinding rate of one component is exactly compensated for by the decrease in the grinding rate of the other component. In this case, the HGI of the blend appears to be additive. However, the composition of the product size intervals is different from the weighted sum of the two products from separate grinding. The overall product size distributions of blends can be obtained by adding the individual size distributions in mixture grinding according to the fractional amount of each present. Since the breakage characteristics of material in a mixture are interdependent, changes in the kinetic parameters must be incorporated into the models for a grinding circuit receiving a heterogeneous feed. An empirical equation can be used for this purpose.

Unfortunately, this is not sufficient because the grinding of coal in the Hardgrove mill exhibits non-first-order grinding kinetics. Consequently, the false time concept for fines accumulation must be adopted. It was shown that the false time concept can be used to predict the grinding behavior of coal blends with reasonable accuracy.

A simulation of locked-cycle grinding for a binary mixture shows that the content of the stronger coal in the recycle increases to make the mill content increasingly richer in the stronger coal, thereby changing the grinding kinetics. Thus, the production rate of the stronger coal increases as the lower breakage rate of the stronger coal is compensated for by the larger quantity. The system eventually attains steady state with a product of 1:1 proportion. However, the higher content of the stronger coal in the mill content produces lower capacity than expected based on the feed composition. Obviously, there is a need for a protocol that will allow a fuel engineer to predict the capacity of a pulverizer that is grinding a coal blend.

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