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An analysis of the energy split for grinding coal/calcite mixture in a ball-and-race mill

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ABSTRACT

Interactions among components in the heterogeneous grinding would change energy consumed characteristics of components if compared with those in the single-component breakage. In this paper, energy split phenomenon for the coarse grinding of super clean anthracite coal (SCAC)/calcite mixture of 2.8–2 mm in the ball-and-race mill is investigated. Before the analysis of experimental results, accuracy of energy split function in terms of time-dependent breakage rate is first discussed. Energy consumed characteristics of grinding in the ball mill and ball-and-race mill are also compared. Breakage model of product t_{10} (yield of progenies in −0.237 mm) vs specific energy is used to describe the energy-size reduction of the single-component and multi-component grinding. Interaction between components is reflected by the comparison of specific energy of components in mixture and single breakage to yield the same product t_{10}. Based on the energy balance, energy split factors of components in different time and mixed conditions are first determined. This parameter shows no change with time. Calcite increases the grinding efficiency of SCAC significantly, with the energy split factor for SCAC ranging from 0.68 to 0.73, which means less specific energy is consumed by SCAC to yield the same t_{10} if compared with the single breakage. As the volumetric ratio of calcite increases in mixture, grinding energy efficiency decreases and energy split factor of calcite increases from 1.70 to 1.83. Soft material reduces the grinding energy efficiency of hard one in the multi-component breakage.

1. Introduction

Breakage of minerals is an energy intensive process. Energy for the comminution of raw coal in power plants consumes nearly 0.5–1% of the gross power generation (Shi et al., 2015). This proportion would increase to over 55% in the mineral processing plant (Narayanan, 1987). In this case, selection of alternative grinding devices is mainly based on the energy saving. New technologies with high energy efficiency, such as the High Pressure Grinding Rolls (HPGR) and horizontal stirred mill of IsaMills, are utilized more widely in the mineral industry. Materials in these grinding devices are usually mixtures of different minerals, such as the production of cement from quartz, kaolin and feldspar, or breakage of ores with various associated minerals, like raw coal or ore containing metals. Hence, liberation of associated minerals and interaction among components make the grinding phenomenon heterogeneous. To circumvent these problems, simulated studies about the heterogeneous grinding have been conducted with mixtures of components in various densities, chemical properties and Moh's Scale of hardness indexes. Due to different densities or chemical reactions, components in sized ground products can be separated, and breakage characteristic of component in a mixture can be investigated. Different breakage behaviors of components in the mixture grinding are because of differences in not only ore properties and split energy, but also energy efficiency, namely fineness of ground products at the given specific energy level.

Holmes and Patching first conducted the comminution of mixture of quartz and limestone in the continuous grinding (Holmes and Patching, 1957). Then, Fuerstenau and Sullivan investigated the energy consumed characterization of mixture grinding of quartz and limestone in a rod mill (Fuerstenau and Sullivan, 1962). Based on the Charles energy-size reduction relationship (Charles, 1957), the same Gaudin-Schuhmann (G-S) size distribution modulus at the single and mixture grinding and constant grindability of constituent minerals, energy consumed for the breakage of binary mineral mixture was calculated.

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Simultaneously, the ternary-mineral mixture grinding of ceramic raw minerals conducted by Ipek showed a good prediction by the modified form of energy-size reduction model of Charles in calculating the energy consumed by each component (Ipek et al., 2005). For minerals in the nearly same density, slopes of grinding time vs size modulus on the log-log plot showed good agreements with weighted average values of distribution moduli of components in mixtures. In this case, energy consumed by component could be calculated based on the volumetric proportion in mixture (Fuerstenau and Sullivan, 1962). However, this method was only suitable for the mixture grinding of components in the same density. Energies consumed by components in different densities cannot be calculated precisely (Venkataraman and Fuerstenau, 1984). Through the comparison of experimental data of homogeneous and heterogeneous grinding, the crucial and important concept of reduced breakage rate function was developed by Herbse and Fuerstenau (1973). This parameter bridged the relationship between mass specific power and breakage rate function, and mathematical models for the energy split factor were developed. These models rely on two important premises: (1) reduced breakage rate function could be used both for the single-component and multi-component grinding, (2) the grinding path of one component in heterogeneous and homogeneous grinding was nearly overlap on the triaxial composition diagram, and reduced breakage rate functions were also the same in both conditions. Detailed derivation of energy split functions had been done by Fuerstenau and other researchers (Kapur and Fuerstenau, 1988; Fuerstenau et al., 1992, 2010) for various grinding experiments. Mathematical models were in terms of time dependent or independent specific rate of breakage and production rate of fines, and they are suitable for both the dry and wet ball mill grinding data of mixture (Fuerstenau et al., 1990). Except for the mixture grinding of components in same size, these models were also used for the heterogeneous grinding of coarse/fine system and gave a good explanation to the change of grinding behavior of coarse particles (Fuerstenau and Abouzeid, 1991; Fuerstenau et al., 2011).

Above successful studies about energy split function in the mixture grinding are mainly conducted on a ball mill. However, for the mixture grinding in a ball-and-race mill (Cho and Peter, 1995) or a High Pressure Grinding Roller (HPGR) (Abouzeid and Fuerstenau, 2009), above mentioned mathematical models were not utilized because the prerequisite did not establish. For instance, overlapped curves in the triaxial composition diagram are worth of discussion because there are only two sieves for the size analyses. As the size distribution of ground products is relatively wide, curves in the triaxial composition diagram cannot describe the size composition well. On the other hand, forces used to break particles in ball mills are mainly via impact and abrasion, but the extruded force is mainly used by the ball-and-race mill and HPGR (Xie et al., 2013). Resistant strengths of mineral to different grinding forces are also not the same. Among these resistant strengths to forces, compressive and tensile strengths are the highest and lowest, and flexure and abrasion strengths are in the middle (He, 2014). In this case, particles would have different breakage behaviors in ball mills and ball-and-race mill. Different grinding mechanisms make the unsuccessful utilization of these energy split factor functions.

Usually, mixture of coals in different Hardgrove indexes is broken by ball-and-race mills in power plants. Different coals are difficult to differentiate with each other, and size distribution of ground products of each coal cannot be got. So it is hard to evaluate the energy split phenomenon during the mixture breakage. On the other hand, associated minerals have an effect on the breakage of raw coal and would make the analyses of energy split complex. In this case, the super clean anthracite coal (SCAC), with lower ash content, is selected to avoid the effect of associated minerals. As the Moh's scale of hardness of calcite is similar to that of SCAC, it is chosen as the other component to represent coals in high ash content. SCAC and calcite are different in density and size distribution of ground products of each component can be obtained by float-sink tests. Before the analysis of experimental results, calculation methods of energy split factor for components during mixture grinding in the ball mill are first discussed. Difference in the breakage mechanism and energy consumed characteristic between ball-and-race mill and ball mill is also analyzed. Following these works, energy split phenomena of components in the mixture grinding in a ball-and-race mill are presented. Based on the difference in density, product t_{10} of each component is obtained. Processes of energy-size reduction of single-component and multi-component grinding are described by the classical breakage model, and interaction between components is expressed by the split energy. Energy split factors of components in the ball-and-race mill at different grinding time are finally calculated.

2. Experiment

2.1. Materials and testing methods

Experiments of multi-component grinding were conducted on a Hardgrove machine, with the addition of a power meter. Densities of SCAC and calcite were 1.25 and 2.8 g cm^{-3}. As the size-reduction of mineral is a process of volumetric breakage, 56 ml materials were used for each test. Mixtures of SCAC and calcite, with volumetric ratios of 7:1, 3:1, 2:1 and 1:1, were prepared. Particles were all in the size of $-2.8+2$ mm. Single components and mixtures were subjected to four different grinding time of 0.5, 1, 1.5 and 2 min. Size distributions of ground products were analyzed by sieving experiments, with sieves from 2 to 0.09 mm in the sieve ratio of $\sqrt{2}$. Size compositions of components were obtained based on float-sink tests of ground products of mixtures, with the dense medium in the density of 1.5 g cm^{-3}. Energy consumed for the breakage of a mixture was calculated by subtracting the non-load energy from the total.

2.2. Confidence analyses of experiments

Though the mass of experimental samples for each mixture breakage is relatively little, specific energy, float-sink tests and size distribution analyses are conducted for mixture breakage and ground products, respectively. Literatures have indicated that variation of sample property would result in large error with experiments in the Hargrove (Shi and Zuo, 2014). But confidence analyses for the mixture breakage of SCAC and calcite are still essential. Repeat experiments were done for the 3:1 SCAC-calcite mixture. Three samples of 3:1 mixture were ground for 1.5 min, and size analyses of ground products and float-sink test of each size fraction were also conducted. Specific energy and product t_{10} of mixture and each component were determined. Mean values of yield of each size fraction, specific energy and product t_{10} were calculated, and the 95% confidence limits were also determined. These results are shown in Table 1. As the calcite has been used up, new samples are prepared. Some difference in breakage characterization exists among calcite samples and experimental results are different with those of previous tests. In this case, confidence analyses are only conducted for repeat experiments. Data in Table 1 demonstrate that experimental errors associated with the energy-size reduction of mixtures in the Hardgrove mill, size analyses and float-sink tests of ground products are small. Most of the 95% confidence limits are 10% of the mean value. As the yield of ground products in coarse size is small, some variation in yield would lead to a big change of this parameter. High repeatability shown in