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Study on Quantitative Separation Method of Grinding Characteristics of Multi-Component Complex Ore

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Abstract: Based on batch grinding method and normalization idea, a conical ball mill is used and a quantitative separation method of grinding characteristics of multi-component complex ore is proposed. The results show that the feed sizes of polymetallic complex ore have an obvious influence on the particle size distribution of intermediate grinding products in the early stage of grinding. However, the influence of the feed size is relatively insignificant on the particle size distribution of intermediate grinding products in the middle and late grinding stages. The grinding product t_{10} is negatively correlated with the feed sizes of ore when the grinding force is applied to the ore. At the same time, it has a simple positive linear relationship with the grinding time. The contribution rates of component minerals pyrrhotite, sphalerite and quartz to the grinding characteristics of the ore are 28.64%~37.74%, 39.93%~51.84%, 16.07%~28.39%, respectively. Therefore, the order of contribution of component minerals to the grinding characteristics of ore is sphalerite > pyrrhotite > quartz. The results provide new insights for the subsequent study of grinding characteristics of multi-component complex ores.

Keywords: batch grinding method; normalization; multi-component complex ore; component minerals; grinding characteristics

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Citation: Yang, J.; Li, Z.; Li, H.; Zhu, P.; Huo, X.; Ma, S. Study on Quantitative Separation Method of Grinding Characteristics of Multi-Component Complex Ore. *Minerals* **2023**, *13*, 517. https://doi.org/10.3390/min13040517

Academic Editors: Josep Oliva and Hernán Anticoi

Received: 18 March 2023
Revised: 4 April 2023
Accepted: 5 April 2023
Published: 6 April 2023

1. Introduction

Grinding is the process of crushing the material through impact and cascade force to reduce the particle sizes of the material. Grinding plays a very important role in the operation of mineral processing plant and undertakes the task of providing selected materials that meet the particle size requirements for subsequent separation operations [1–3]. The primary purpose of grinding is to dissociate the useful minerals closely embedded in the ore from gangue minerals. However, the grinding materials are mostly multi-component complex ores composed of different minerals in the process of most ball milling operations. Due to the differences in chemical composition, microstructure, hardness and other aspects of different minerals in the ores, the ores containing different minerals will show different grinding characteristics [4–6]. This phenomenon is particularly prominent in industries such as mining, cement and ceramics. Therefore, the study of the grinding characteristics of multi-component complex ore is of great significance to optimize the grinding process, improve grinding efficiency and reduce grinding cost. Scholars have conducted a lot of research on this issue. LEE et al. took pyrophyllite as the research object, that evaluated the grinding particle size distribution and chemical composition of pyrophyllite based on the grinding population balance kinetic. Additionally, the relationship between the grinding characteristics of pyrophyllite and the content of Al_2O_3 was obtained [7]. Owusu et al. took waste printed circuit boards as the research object, and evaluated the influence of different mill speed, screen size and feed size on its grinding characteristics based on the grinding overall equilibrium dynamics and the Rosin–Rammler equation in order to determine the optimal grinding conditions of waste printed circuit boards in a hammer mill [8]. Wonjae et al. took iron ore and quartz as the research object, and realized the prediction of the grinding characteristics of iron ore and quartz with the variation of grinding time and pulp concentration, applying acoustic sensors to measure the acoustic changes in the working process of ball mill [9]. Saija et al. studied waterless operations from mine to mill [10]. Anderson et al. considered a new grinding process that only uses HPGR as the regrinding stage after concentration [11]. According to the above description, the grinding characteristics of ore have been completely studied by experts and scholars. However, most of the previous researches focus on the actual grinding characteristics of ore, and a few reports have been made on the connection between the grinding characteristics of ore and its component minerals. Yang et al. have studied the qualitative impact of component minerals on the grinding of polymetallic ores, but have not studied the qualitative impact [12]. In order to solve this problem, the polymetallic complex ore and its main component minerals, pyrrhotite, sphalerite and quartz, were taken as the research objects in this paper. Based on batch grinding method and normalization idea, a quantitative separation method of multi-component complex ores of grinding characteristics is proposed by taking grinding product t_{10} as the parameter characterizing material grinding characteristics. The results provide new insights for the subsequent study of grinding characteristics of multi-component complex ores to provide a data and theoretical basis for quantifying the impact of all constituent minerals and their content on the grinding contribution rate of a certain ore.

2. Materials and Methods

2.1. Materials

The test sample is taken from a polymetallic complex ore in Guangxi, whose main mineral components are pyrrhotite, sphalerite, quartz, etc. [13]. In order to ensure the representativeness and simplicity of the test, the polymetallic complex ore is simplified to be composed of the above three pure minerals, which is conducive to the quantitative separation of grinding characteristics of multi-component complex ore. The component minerals of the selected ore are pure minerals purchased from an enterprise in Guangzhou. The surface of ore and component minerals are cleaned, dried, crushed, screened, mixed and divided. The samples of four single particle sizes (−4.75 + 3.35 mm, −3.35 + 2.36 mm, −2.36 + 1.7 mm, −1.7 + 1.18 mm) are prepared and bagged at 300 g per bag. The test equipment is the (XMQ-ϕ240 × 90A) conical ball mill.

2.2. Methods

2.2.1. t_{10} Parameter

The meaning of t_{xx} is whose particle size is 1/xx of the feed particle size under sieve cumulative yield of the product. The literature shows [14,15] that if the products t_{10} can be obtained, the products t_{xx} can be also obtained, and they can represent a complete product particle size distribution. Because the relationship of t_{10}–t_{xx} is only related to the nature of the material [16], t_{10} is chosen as the fulcrum of quantitative separation of contribution rate of ore grinding characteristics, which can reflect the grinding characteristics of materials more completely.

2.2.2. Normalization Method

The normalization method refers to how the absolute value of a variable in a physical system is transformed into a relative value relationship, which is widely used in the field of computation. In the field of grinding, the idea of this method is applied in the cylindrical ball mil for the quantitative separation of impact and abrasion contribution rate by Yang [17], and its feasibility and rationality had been verified. In this paper, the basis of the normalization idea is that the polymetallic complex ore is a mixture constructed of multiple component minerals. Therefore, the grinding characteristics of ore are the synthesis of the grinding characteristics of various component minerals. That is to say, no matter how the grinding characteristics of polymetallic complex ore change, the contribution rate of the component minerals to its grinding characteristics is 100%. Based on the idea and principle of normalization, this paper also quotes the coupling factor ξ, which is defined as the component mineral grinding product t_{10} divided by the polymetallic complex ore grinding product t_{10} in the grinding process. In relation to the actual ore grinding process, the coupling factor ξ can be explained. The grinding characteristics of complex polymetallic ores are the result of the interaction of multiple component minerals. When the ore is grinding in the mill, the soft minerals in the ore are broken first because of the weak impact and abrasion resistance of the soft component minerals. The surface area of ore is increased, which is conducive to the mill medium to crush it. During the second grinding, the probability of crushing the soft component minerals by the mill will decrease because the particle size of the soft component minerals becomes smaller in the ore, and the hard component minerals will play a leading role in the grinding characteristics of the ore; thus, that the overall strength of the ore increases. Such a process goes round and round, the former is the process of enhancing the coupling grinding effect of component minerals, the latter is the process of weakening the coupling grinding effect. Therefore, when a complex polymetallic ore is grinding, it can be defined as a complex coupling process in which the component minerals of the ore change with grinding time. The coupling factor ξ can be calculated as follows:

$$\xi = \frac{t_p + t_s + t_q}{t_c} \tag{1}$$

Based on the theoretical analysis in Section 2.2.1, Formulas (2)–(5) are further defined. In the grinding process, the contribution rate of component mineral pyrrhotite to the grinding product t_{10} is C_p, %, that is, the contribution rate of component mineral pyrrhotite to the grinding characteristics of ore. The contribution rate of component mineral sphalerite to ore grinding product t_{10} is C_s, %, that is, the contribution rate of component mineral sphalerite to ore grinding characteristics. The contribution rate of quartz to the grinding product t_{10} is C_q, %, that is, the contribution rate of constituent mineral quartz to the grinding characteristics of ore. The relationship is shown as follows:

$$C_P = \frac{t_P}{\xi \cdot t_c} \times 100\% \tag{2}$$

$$C_s = \frac{t_s}{\xi \cdot t_c} \times 100\% \tag{3}$$

$$C_q = \frac{t_q}{\xi \cdot t_c} \times 100\% \tag{4}$$

$$C_p + C_S + C_q = 1 \tag{5}$$

where ξ is the coupling factor of the action of each component mineral on the ore in the grinding process; t_c means t_{10}, % of ore grinding products; t_p means component mineral pyrrhotite grinding mineral products t_{10}, %; t_s means component mineral sphalerite grinding mineral products t_{10}, %; t_q means component mineral quartz grinding mineral products t_{10}, %.

The grinding contribution rate formula was used to quantify the impact of component minerals (pyrrhotite, sphalerite, quartz) on the grinding of polymetallic ores, which is a novelty proposed in this paper.

3. Experimental Theory Analysis

3.1. Particle Size Distribution

The batch grinding method was used when the mill rotation rate was 70%, the medium filling rate was 38%, and the grinding concentration was 70%. The grinding tests of the polymetallic complex ore were carried out under different grinding times (1 min, 2 min, 4 min, 6 min, 8 min) at the feed sizes of −4.75 + 3.35 mm, −3.35 + 2.36 mm, −2.36 + 1.70 mm, −1.70 + 1.18 mm. The grinding completion test samples are screened to obtain the particle size distribution of grinding products for ores of different feed sizes. The cumulative yield curve of ore grinding products under sieve is drawn in semilog coordinate, and the results are shown in Figure 1.

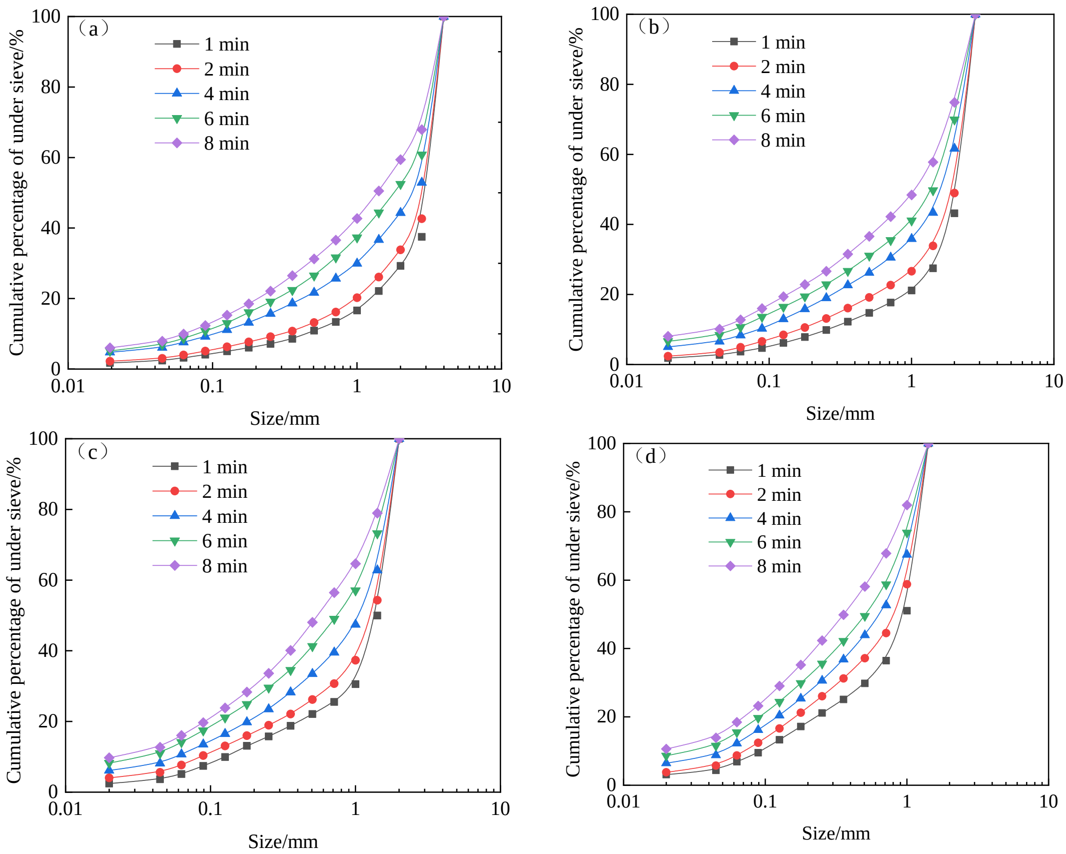

Figure 1. Particle size distribution of grinding products for complex polymetallic ores ((**a**): −4.75 + 3.35 mm, (**b**): −3.35 + 2.36 mm, (**c**): −2.36 + 1.70 mm, (**d**): −1.70 + 1.18 mm).

According to the analysis in Figure 1a–d, under the conditions of the same feed sizes and different grinding time, the particle size distribution curve of the grinding products of polymetallic complex ores was essentially the same, and decreases approximately exponentially. With the extension of grinding time, the particle size distribution curve of grinding products gradually shifted upward. This is because in the working process of the mill, the longer the ore stays in the mill, the energy transmitted by the grinding medium of the ore would gradually increase. Therefore, under the same condition of feed sizes, the longer the ore was subjected to the grinding force in the mill, the more completely the grinding products is ground. In addition, the particle size distribution curve of five grinding products of each particle size shows that the two sides are close to each other and the middle distance was loose. This shows that under different grinding time, when the ore is subjected to grinding force, the proportion of intermediate fraction is larger than that of fine fraction and coarse fraction. By analyzing Figure 1a–d again, it could be seen that when the grinding time was 4, 6, and 8 min, the distance between the particle size distribution curves of the intermediate particle size grinding products of different feed sizes are relatively average. When the grinding time was 1 min and 2 min, with the decrease in the feed sizes, the spacing of the particle size distribution curve of the intermediate particle size was gradually opened, and when the feed size was −1.70 + 1.18 mm, the spacing of the particle size distribution curve of the intermediate particle size tends to be equal in each grinding time. It can be seen from the analysis that in the early stage of grinding, the size of the feed sizes of the ore has a significant effect on the particle size distribution of the ore intermediate grade grinding products. While in the middle and late stages of grinding, the size of the feed sizes of the ore has a relatively insignificant effect on the particle size distribution of the ore intermediate grade grinding products.

3.2. Particle Size Characteristic

Based on the grinding data in Section 3.1, the grinding product t_{10} of polymetallic complex ores with different feed sizes were calculated, and the relation curve between t_{10} and grinding time was drawn. The result is shown in Figure 2.

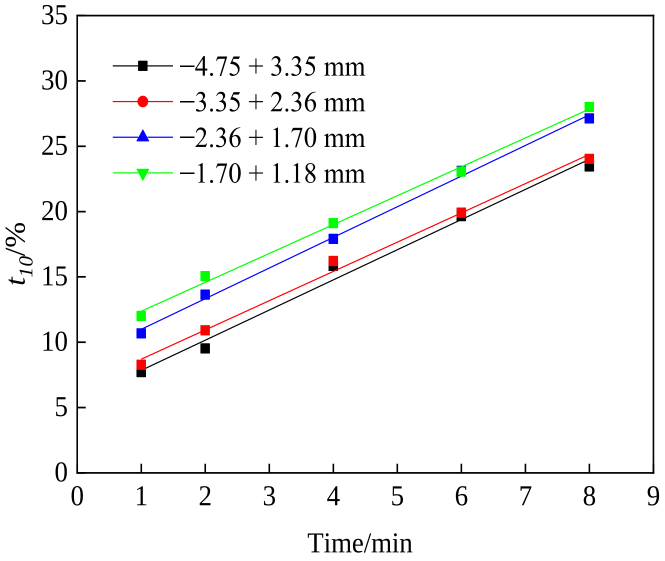

Figure 2. The relationship between grinding products t_{10} and grinding time of polymetallic complex ore with different feed sizes.

According to the analysis in Figure 2, when the polymetallic complex ore is subjected to grinding force, the grinding product t_{10} of the ore exhibits a simple linear relationship with the grinding time, and with the extension of grinding time, the product t_{10} of different feed sizes increases linearly. At the same time, by observing the linear slope of t_{10} of different feed sizes, it can be seen that the slope is approximately equal, which indicates that there is no obvious rule between the slope of t_{10} of ore grinding products and the size of the feed sizes. That is, the strong or weak of the grinding force on the ore has no obvious relationship with the feed sizes. By analyzing Figure 2 again, it can be seen that the grinding product t_{10} of the ore increases with the decrease in the feed sizes. That is, the grinding product t_{10} of the ore is negatively correlated with the feed sizes. At the same time, by comparing the changes of t_{10} curves of grinding products of four feed sizes, it could be found that when the feed size was −4.75 + 3.35 mm, −3.35 + 2.36 mm, and the t_{10} curve spacing of grinding products was closer. When the feed size was −2.36 + 1.70 mm and −1.70 + 1.18 mm, the grinding products t_{10} curve spacing of two size fractions is closer. Comprehensive analysis shows that among the four feed sizes of the ore. The grinding particle size characteristics of −4.75 + 3.35 mm and −3.35 + 2.36 mm for ore is more similar. The grinding particle size characteristics of −2.36 + 1.70 mm and −1.70 + 1.18 mm for ore are more similar. It can also be seen from Figure 2 that there is a wide gap between the second and third approximation lines, which indicates that the causes of crushing of coarse and fine particle sizes may be different, and fine particle sizes are more likely to be crushed than coarse particle sizes.

3.3. Quantitative Separation of Grinding Characteristics

The component minerals pyrrhotite, sphalerite and quartz of the polymetallic complex ore were taken for batch grinding test according to Section 3.1 grinding test conditions. Component mineral grinding product t_{10} was calculated based on the particle size distribution data of grinding product obtained. Based on Section 3.2 and above component mineral grinding products t_{10} data, the contribution rate of grinding characteristics of polymetallic complex ores was quantified and separated according to Section 2.2.2 normalization idea. The quantitative separation results of ore grinding characteristics were shown in Figures 3 and 4 (The E_{yc} in the figure is the contribution rate of component minerals to ore grinding characteristics, %).

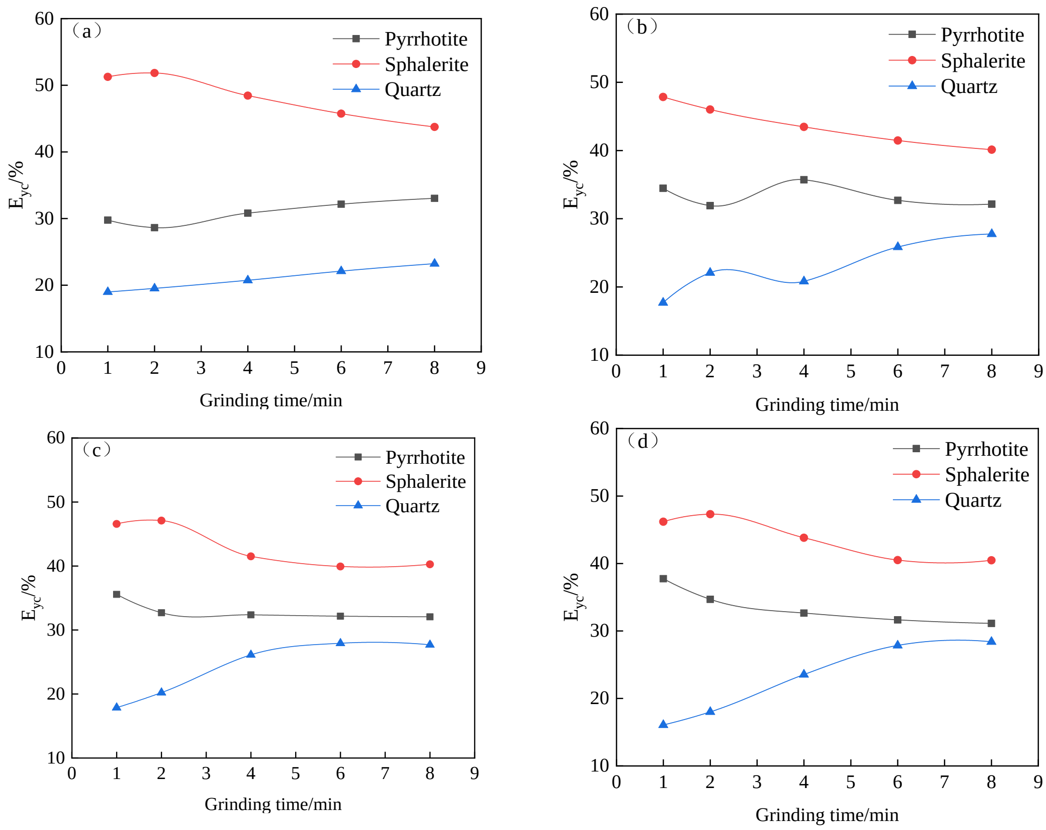

Figure 3. The contribution rate of component minerals for ore grinding characteristics at different feed sizes ((**a**): −4.75 + 3.35 mm, (**b**): −3.35 + 2.36 mm, (**c**): −2.36 + 1.70 mm, (**d**): −1.70 + 1.18 mm).

According to the analysis in Figure 3a–d, the contribution rate of component sphalerite minerals for ore grinding characteristics showed a downward trend with the extension of grinding time under the same feed sizes, and the contribution rate of constituent mineral quartz for ore properties is on the rise. The contribution rate of component pyrrhotite for the grinding characteristics of ore at the feed sizes of −2.36 + 1.70 mm and −1.70 + 1.18 mm showed an overall decreasing trend, the overall trend is approximately unchanged at the feed size of −3.35 + 2.36 mm, and the overall trend is increasing at the feed size of −4.75 + 3.35 mm. Additionally, the contribution curves of the three component minerals for the ore grinding characteristics gradually approach with the extension of grinding time. Again, by analyzing Figure 3a–d, it can be seen that when the feed size is −4.75 + 3.35 mm, the contribution rates of component minerals pyrrhotite, sphalerite and quartz for the grinding characteristics of the ore range from 28.64%~33.03%, 43.74%~51.84%, 18.99%~23.23%, respectively. When the feed size is −3.35 + 2.36 mm, the contribution rates of the three component minerals for the grinding characteristics of the ore range from 31.91%~35.71%, 40.12%~47.85%, 17.69%~27.75%, respectively. When the feed size is −2.36 + 1.70 mm, the contribution rates of the three component minerals for the grinding characteristics of the ore range from 32.06%~35.57%, 39.93%~47.10%, 17.86%~27.92%, respectively. When the feed size is −1.70 + 1.18 mm, the contribution rates of the three component minerals for the grinding characteristics of the ore range from 31.12%~37.74%, 40.48%~47.31%, 16.07%~28.39%, respectively. By comparing the contribution rate of component minerals of different feed sizes for the grinding characteristics of the ore, it can be seen that the order of contribution of component minerals for the grinding characteristics of the ore was sphalerite > pyrrhotite > quartz during the same grinding time. The Mohs hardness of sphalerite is 3.5, that of magnetic pyrite is 3.5–4.5, and that of quartz is 7. From the perspective of mineral hardness, hardness is indeed related to the contribution rate of grinding. This is a significant rule. In subsequent research, we will further consider the quantitative impact of mineral Mohs hardness on the grinding contribution rate.

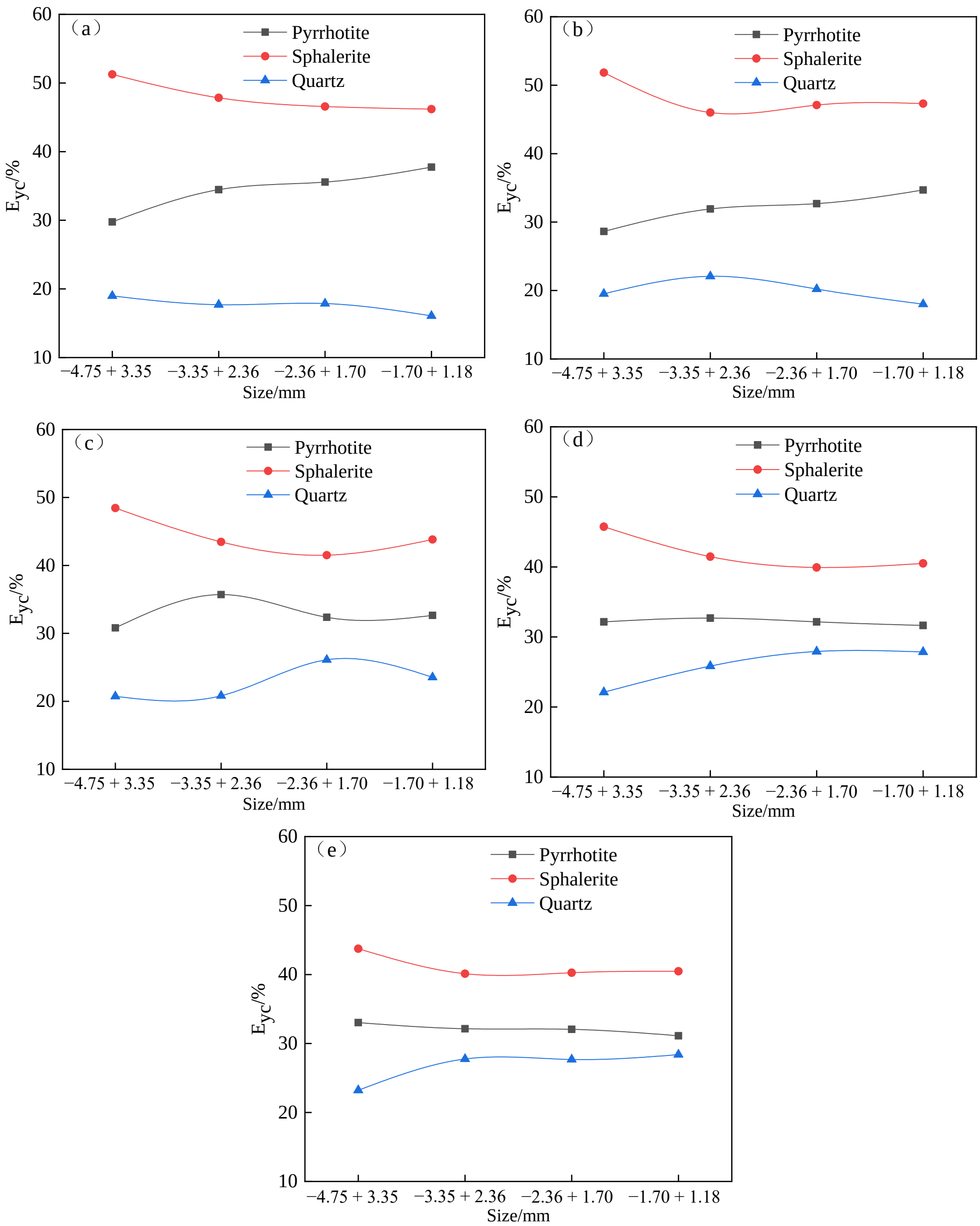

Figure 4. Contribution rate of component minerals with different grinding time to ore grinding characteristics ((**a**): 1 min, (**b**): 2 min, (**c**): 4 min, (**d**): 6 min, (**e**): 8 min).

According to the analysis in Figure 4a–e, when the feed size decreases, the contribution rate of component sphalerite for the ore grinding in the same grinding time range showed a decreasing trend. When the grinding time is 1 and 2 min, the contribution rate of component pyrrhotite for the ore is showed an overall increasing trend. Additionally, when the grinding time was 4, 6 and 8 min, the overall change is approximately unchanged. When the grinding time is 1 and 2 min, the contribution rate of constituent mineral quartz for the ore is showed a downward trend as a whole. Additionally, when the grinding time is 4, 6 and 8 min, it showed an upward trend. In the early stage of grinding, with the decrease in feed sizes, the contribution rate of component pyrrhotite for ore grinding characteristics is gradually close to component sphalerite, but gradually away from component quartz. In the middle stage of grinding, the contribution rate of the three component minerals for the ore gradually approaches and then gradually moves away with the decrease in the feed sizes. At the late grinding stage, the contributions of the three component minerals to the ore gradually approach with the decrease in the feed sizes. Based on the analysis of Figure 4a–e, it can be seen that when the grinding time is 1 min, the contribution rates of component pyrrhotite, sphalerite and quartz for the grinding characteristics range from 29.76%~37.74%, 46.19%~51.26%, 16.07%~18.99%, respectively. When the grinding time is 2 min, the contribution rates of component pyrrhotite, sphalerite and quartz for the grinding characteristics is 28.64%~34.69%, 46.01%~51.84%, 18.01%~22.08%, respectively. When the grinding time is 4 min, the contribution rates of component pyrrhotite, sphalerite and quartz for the grinding characteristics are in the following ranges: 30.81%~34.69%, 46.01%~51.84%, 18.01%~22.08%, respectively. When the grinding time is 6 min, the contribution rates of component pyrrhotite, sphalerite and quartz to the grinding characteristics are 31.65%~32.69%, 39.93%~45.74%, 22.11%~27.92%, respectively. When the grinding time is 8 min, the contribution rates of component pyrrhotite, sphalerite and quartz to the grinding characteristics are 31.12%~33.03%, 40.12%~43.74%, 23.23%~28.39%, respectively. By comparing with the analysis of the contribution range of component minerals to the grinding characteristics for the ore at different grinding times, it can be seen that the order of contribution of component minerals to the grinding characteristics of the ore was sphalerite > pyrrhotite > quartz within the same range of the feed sizes. Through comprehensive analysis of the specific contribution range of component minerals to the ore in Figures 3a–d and 4a–e, the contribution rate of ore grinding characteristics under different feed sizes of the same component minerals and different grinding time is combined to analyze. Thus, the contribution rates of component minerals pyrrhotite, sphalerite and quartz to the grinding characteristics for the ore are 28.64%~37.74%, 39.93%~51.84%, 16.07%~28.39%, respectively.

4. Conclusions

(1) The particle size distribution curves of grinding products of multi-metal complex ores at the same feed sizes and different grinding time are essentially identical, and they decrease exponentially. The particle size distribution curve of grinding products is gradually shifted upward with the extension of grinding time. When the ore is subjected to grinding force at different grinding times, the proportion of intermediate sizes fraction is larger than that of fine sizes fraction and coarse sizes fraction. In the early stage of grinding, the size of the feed sizes of the ore has a significant effect on the particle size distribution of intermediate grinding products. However, in the middle and late grinding stages, the influence of the size of the feed sizes of the ore on the particle size distribution of intermediate grinding products is relatively insignificant.

(2) When the polymetallic complex ore is subjected to grinding force, the grinding products t_{10} is negatively correlated with the feed sizes of ore. There is a simple linear relationship between the grinding product t_{10} and the grinding time of the ore. With the extension of grinding time, the t_{10} of the products of different feed size increases linearly. At the same time, by observing the slope of line t_{10} of products with different

feed sizes, it can be seen that the grinding force for the ore has no obvious relationship with the size of the feed sizes.

(3) Under different feed size and grinding time conditions, the contribution rates of component minerals pyrrhotite, sphalerite and quartz for grinding characteristics of the ore are 28.64%~37.74%, 39.93%~51.84%, 16.07%~28.39%, respectively. The order of contribution of component minerals for grinding characteristics of the ore is sphalerite > pyrrhotite > quartz. The results provide new insights for the subsequent study of grinding characteristics of multi-component complex ores.

Author Contributions: Conceptualization, J.Y. and S.M.; Data curation, Z.L. and J.Y.; Formal analysis, X.H. and P.Z.; Funding acquisition, S.M.; Investigation, P.Z. and J.Y.; Methodology, J.Y. and S.M.; Project administration, J.Y. and S.M.; Validation, H.L. and J.Y.; Writing—Original draft, Z.L. and J.Y.; Writing—Review and editing, J.Y. and H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52274258, No. 51874105).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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