

Research Article

Effect of Microwave Pretreatment on Grindability of Lead-Zinc Ore

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The influence of microwave pretreatment on grindability of lead-zinc ore was studied through comparison analysis on the changes of particle size distribution, percentage of below 0.074 mm, energy consumption, and other indexes of grinding products before and after microwave pretreatment in the ball milling process. The results showed that the grindability of lead-zinc ore was improved obviously by microwave pretreatment. The particle size distribution curve of the grinding products was obviously higher than that of the samples without microwave irradiation. The yield of size fraction below 0.074 mm was also improved in a certain degree. Pulsed microwave irradiation was more effective than continuous microwave irradiation when other microwave parameters were consistent. The comprehensive energy consumption of lead-zinc ore pretreated by different microwave parameters was lower than that without microwave irradiation under the same grinding fineness. The total energy consumption was down by 30.1% when irradiated for 15 s at 7 kW power, and it was lower than that without microwave irradiated. The results showed that pulsed microwave pretreatment was more effective in reducing the comprehensive energy consumption of grinding process for lead-zinc ore. And water quenching after microwave irradiation can improve the grindability and reduce the energy consumption of grinding for lead-zinc ore.

1. Introduction

The crushing and grinding of ore is considered to be a process of high energy consumption and low efficiency. There are two indicators to evaluate the efficiency of grinding. One is the particle size distribution, and the other is the liberation degree of grinding products [1]. The essence of grinding is ore properties. Changing the mechanical properties of ore [2, 3], improving the liberation degree of useful minerals, and enhancing the grinding efficiency have always been the focus of scholars [4, 5].

Previous studies indicate that the heat pretreatment can reduce the energy consumption of grinding effectively and improve the liberation degree of useful minerals [6–8].

Compared with conventional heating, microwave pretreatment has the advantages of fast heating rate [9, 10], selective heating, uniformity heating, and so on [11]. Because of the different dielectric loss factors of different minerals, the microwave absorption capacity of mineral particles is not the same [12, 13]. Thus, thermal stress is induced by the temperature difference between mineral particles, which leads to cracks in the grain boundary of mineral particles and promotes grinding and dissociating of useful minerals [14, 15].

Microwave pretreatment can improve the grinding property and grinding efficiency of ore [16]. However, most researchers pretreat ore with continuous microwave [17, 18]. From the pretreatment effect of the ore [19], it has the

disadvantage of high energy consumption for continuous microwave irradiation, and high temperature may even cause changes in the crystal structure of some useful minerals, thus affecting the efficiency of subsequent processes.

It is found that pulse microwave irradiation is a more effective method to reduce the mechanical strength of ore and improve the degree of mineral dissociation. [20] found that microcracks produced in breccia uranium ore with pulsed microwave pretreatment was the fundamental reason for improving its grindability. [21] found that pulsed microwave with high power would be more efficient than continuous microwave for treating fine-grained ores. [22] irradiated pyrite with continuous microwave and pulsed microwave, respectively, and found pulsed microwave could be more effective on weakening the ore. In addition, it was found that the grinding property and energy consumption of the metallurgical coke pretreated by pulsed microwave for a short time were better than by continuous microwave pretreatment [23]. So it can be seen pulsed microwave pretreatment is an important subject in the area of improving the grinding of ore, which has a wide range of potential applications. Pulsed microwaves are obtained by applying high-voltage pulses of microsecond to millisecond width to a magnetron. Its pulse power can reach tens of kilowatts or even several megawatts, while the average power is only a few kilowatts. When such microwave energy is added to the treated ore, the ore will be irradiated by high-energy microwave in a very short period of time, and the grain boundary fracture will occur to various wave-absorbing minerals in the ore under the action of thermal stress, thus reducing the mechanical strength of the ore [24] and improving the degree of mineral dissociation. At present, there are few researches on the grinding ability of pulsed microwave pretreatment for lead-zinc ore, which points out the direction of this experiment.

So the objective of this research was to compare and analyze the changes of the particle size distribution, percentage of below 0.074 mm [25], grinding energy consumption, and other indexes before and after the continuous and pulsed microwave pretreatment of lead-zinc ore and to reveal the influence of microwave pretreatment on the grindability of lead-zinc ore.

2. Experimental

2.1. Raw Materials. The lead-zinc ore from Hunan province in China was crushed to 1-2 mm by the jaw crusher and then divided by the cone quartering method for grinding test. The mineral composition of lead-zinc ore was analyzed by X-ray diffractometer (XRD), and the results are shown in Figure 1. Microwave digestion was used, hydrochloric acid and hydrogen peroxide solution was used to digest the lead-zinc ore sample, and then, atomic absorption spectrograph was used to determine the content of lead, zinc, and other metals in the digestion solution. Through chemical test and analysis, the chemical composition of lead and zinc ores is shown in Table 1. Table 1 shows that the petrochemical composition complex, lead-zinc mine of valuable element content is 2.9% and 4.80% of lead and zinc, respectively, and contains a lot of sulfur, iron, and silicon; there is a small amount of

calcium; the content is 30.29%, 18.68%, 17.98%, and 2.03%, respectively; the ore belongs to contain lead and zinc sulfide ores; the main metal mineral of galena and sphalerite and gangue minerals are mainly quartz.

2.2. Equipment. The box-type microwave heating device used in this experiment was developed independently by the key discipline laboratory for national defense for biotechnology in uranium mining and hydrometallurgy from university of South China. Its power is continuously adjustable in the range of 1-70 kW, and the frequency is 2450 MHz. As shown in Figure 2, the size of sagger used to load the ore for microwave irradiation is 168 × 130 × 45 mm, and the loading capacity of each sagger is 2.5 kg. 1 is the magnetron, 2 is the door of cavity, 3 is the platform, 4 is touch screen of human-machine interface operation, 5 is the power supply of the microwave tube, 6 is the frequency converter, 7 is the cooling water tube, and 8 is the microwave resonant heating cavity. The grinding test was carried out by planetary ball mill from German Retsch company, as shown in Figure 3.

2.3. Test Plan. The lead-zinc ore was crushed to 1-2 mm by the jaw crusher and then divided by the cone quartering method for grinding test. Seven parts of ore samples were marked as 1#, 2#, 3#, 4#, 5#, 6#, and 7#, respectively. The detailed test plan was shown in Table 2. Seven parts of lead-zinc ore samples were pretreated under microwave with different irradiation parameters. Each part was weighed 200 grams and put into planetary ball mill to grind for 10 min with speed of 400 rad/min.

The yield of each particle was obtained by analyzing the ore grinding products with standard sieves of 24 mesh, 28 mesh, 40 mesh, 55 mesh, 60 mesh, 80 mesh, 100 mesh, 120 mesh, 150 mesh, 190 mesh, and 200 mesh, respectively. Repeat the experiment many times, particle size distribution curves of lead-zinc ore were drawn for different microwave irradiation parameters, and it revealed the influence law of microwave pretreatment and cooling methods on the particle size of lead-zinc ore after ball milling.

3. Results and Discussion

It can be seen that the coarse fraction was relatively large, and the percentage of below 0.074 mm after ball milling was only 36.08% without microwave pretreatment. The content of coarse fraction with microwave pretreatment after ball grinding for 10 minutes decreased gradually. The grinding products were finer, and the percentage content of grinding products below 0.074 mm was larger by increasing microwave power and changing the cooling method when the rest grinding conditions were completely the same.

3.1. Effect of Continuous Microwave Pretreatment on Particle Size of Grinding Products. Figure 4 showed the effect of continuous microwave pretreatment on size fraction distribution of grinding products for lead-zinc ore. It can be seen that the contents of coarse and medium size fraction (380-600 μm and 106-120 μm) were 6.93% and 7.90%, respectively, after ball milling without microwave irradiation, and the content of fine fraction below 74 μm was 36.08%. When the lead-

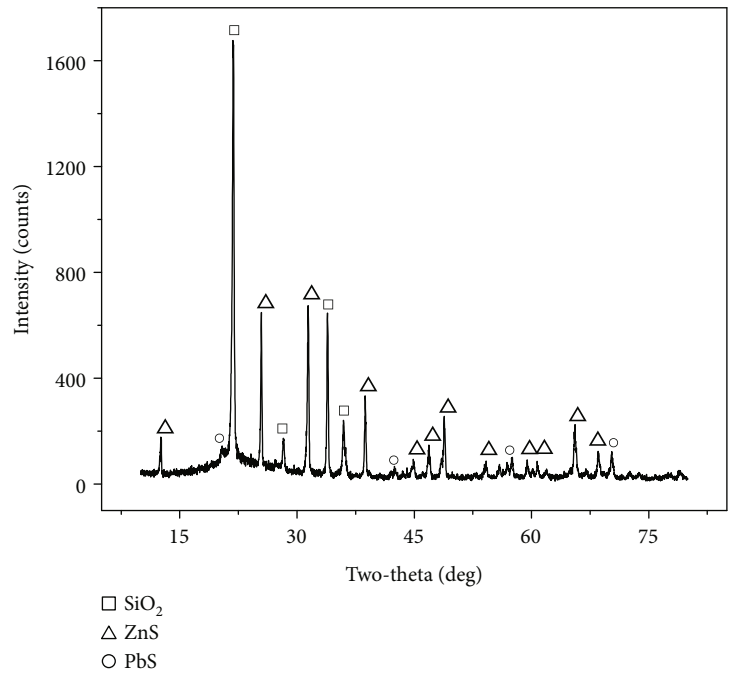


FIGURE 1: X-ray diffraction pattern of lead-zinc ore for grinding test.

TABLE 1: Main chemical composition of lead-zinc ore.

Component	Pb	Zn	S	Fe	Si	O	Ca	C	Cu
Content (%)	4.80	2.90	30.29	18.68	17.98	19.32	2.03	1.42	0.30
Component	P	F	As	Al	Ba	K	Mg	Na	
Content (%)	0.31	0.05	0.17	0.81	0.06	0.40	0.31	0.18	

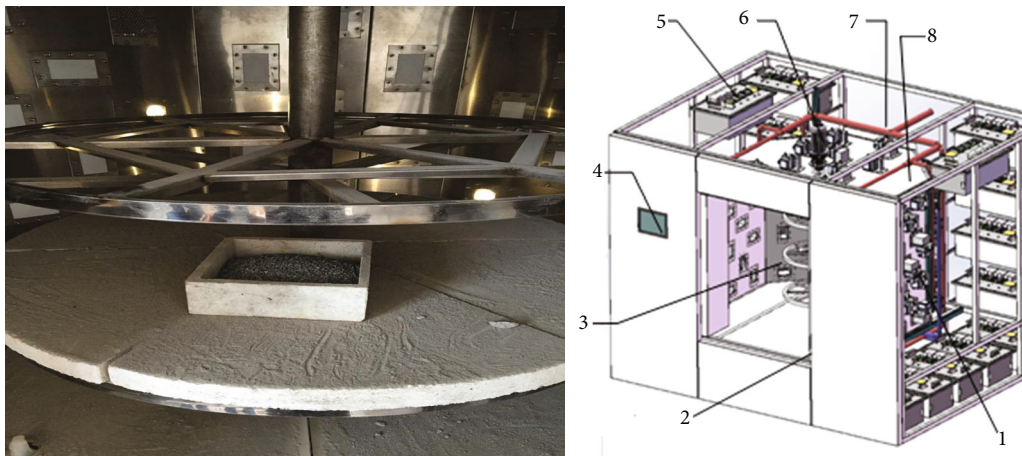


FIGURE 2: Internal diagram and three-dimensional diagram of the microwave heating device.

zinc ore was irradiated by continuous microwave with power of 800 W, the contents of coarse and medium size fraction decreased gradually after natural cooling, but not so obvious. For example, the contents of size fraction (380-600 μm and 106-120 μm) were 5.86% and 5.19%, respectively, but the content of fine fraction below 74 μm was 41.36%, which increased obviously. As the power of continuous

microwave was increased to 7 kW, the content of coarse and medium size fraction decreased gradually, and the fine fraction content increased gradually, where the content of below 74 μm increased to 48.61%. By comparing the effects of 800 W and 7 kW microwave power on the ore size distribution after grinding, it could be seen that the ore treated by 7 kW microwave power was more conducive to grinding



FIGURE 3: Planetary ball mill with four platforms.

and thus to mineral disintegration under less irradiation time.

Figure 5 reflected the influence of continuous microwave pretreatment on the particle size cumulative percentage of grinding products for lead-zinc ore. As shown in Figure 5, the particle size distribution curve of the grinding products after continuous microwave pretreatment was above that without microwave irradiation obviously. It is indicated that continuous microwave pretreatment can improve the grindability of lead-zinc ore, and the particle size of ore samples becomes finer with the increase of microwave power. It could be that the lead-zinc minerals were easy to absorb microwave energy and converted it into thermal energy under microwave irradiation, but the gangue minerals were not easy to absorb microwave energy. Then, thermal stress was formed in the ore due to the temperature gradient, which led to microcracks in the grain boundary of different minerals, reducing the mechanical strength of the ore and improving the grinding effect.

The surface of lead-zinc ore was characterized by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) after continuous microwave irradiation, as shown in Figure 6. The results of SEM and EDS analyses were as follows. Figure 6(a) showed that the bright zone contained Pb and S elements, which should be galena, and there were a lot of cracks on the surface of the bright zone, which may be caused by thermal stress between the metallic minerals and gangue minerals after microwave irradiation. Figure 6(b) showed that the dark zone contained Zn and S elements, which should be sphalerite, and there were also some cracks

on its surface. In addition, under the scanning electron microscope, there were clear cracks appearing on the bright and dark borders between the two metallic minerals. It proved that the microwave treatment caused cracks between different minerals in the lead-zinc ore, which could effectively promote the dissociation of metallic minerals and gangue minerals, leading to the reduction of the strength of lead-zinc ore, improving the grinding effect.

3.2. Effect of Pulsed Microwave Pretreatment on Particle Size of Grinding Products. The influence of pulsed microwave pretreatment on size fraction distribution of grinding products for lead-zinc ore was shown in Figure 7. It can be seen that the contents of coarse and medium size fraction ($250\text{-}260\ \mu\text{m}$ and $106\text{-}120\ \mu\text{m}$) were 6.48% and 7.90%, respectively, after ball milling without microwave irradiation, and the content of fine fraction below $74\ \mu\text{m}$ was 36.08%. When the lead-zinc ore was irradiated by pulsed microwave with nature cooling under the condition of pulsed microwave of 7 kW, pulse width of 1 ms, and working frequency of 500 Hz, the contents of size fraction ($250\text{-}260\ \mu\text{m}$ and $106\text{-}120\ \mu\text{m}$) were 2.07% and 2.93%, respectively, and the content of fine fraction below $74\ \mu\text{m}$ was 49.58% which increased obviously.

Figure 7 shows the influence of pulsed microwave pretreatment on the percentage of particle size accumulation of lead-zinc ores. It can be seen that the particle size distribution curve of the grinding products with pulsed microwave pretreatment was above that without microwave irradiation obviously. It indicates that pulsed microwave pretreatment also can improve the grinding efficiency of lead-zinc ore.

3.3. Effect of Cooling Method on Particle Size of Grinding Products. Figure 8 showed the influence of cooling method on size fraction distribution of grinding products after continuous microwave pretreatment. It can be seen from Figure 8 that water quenching had a significant influence on the grinding effect of lead-zinc ore irradiated by continuous microwave with power of 800 W for 70 seconds. The yield of fine fraction of grinding products after water quenching was obviously higher than natural cooling. The effect of water quenching on grinding was more remarkable than that of natural cooling when lead-zinc ore was irradiated by continuous microwave with power of 7 kW for 15 seconds. The yields of the size fraction ($380\text{-}600\ \mu\text{m}$) with water quenching after continuous microwave pretreatment decreased from 5.19% to 3.83%, and the yields of the fine fraction below $74\ \mu\text{m}$ increased from 48.61% to 51.46% compared to natural cooling. The effect of water quenching on the grinding of lead-zinc ore was more remarkable than natural cooling whether it was pretreated by continuous microwave or pulsed microwave. It could be that the water quenching can prevent healing microcracks formed along the mineral grains due to thermal stress generated by microwave irradiation. At the same time, water quenching also caused a sudden drop in temperature in and outside the ore, which further expanded the original grain boundary cracks of the minerals.

Figure 9 showed the influence of cooling method on size fraction distribution of grinding products after pulsed microwave pretreatment with high power. As shown in Figure 9,

TABLE 2: Grinding test plan of lead-zinc ore with microwave pretreatment.

Test label	Microwave pretreatment parameters			Grinding parameters		
	Microwave type	Power (kW)	Time (s)	Cooling method	Speed (rad/min)	Grinding time (min)
1#	No microwave irradiation	/	/	/	400	10
2#	Continuous microwave	0.8	70	Nature cooling	400	10
3#	Continuous microwave	0.8	70	Water quenching	400	10
4#	Continuous microwave	7	15	Nature cooling	400	10
5#	Continuous microwave	7	15	Water quenching	400	10
6#	Pulsed microwave, pulse width was 1 ms, working frequency was 500 Hz	7 (peak)	15	Nature cooling	400	10
7#	Pulsed microwave, pulse width was 1 ms, working frequency was 500 Hz	7 (peak)	15	Water quenching	400	10

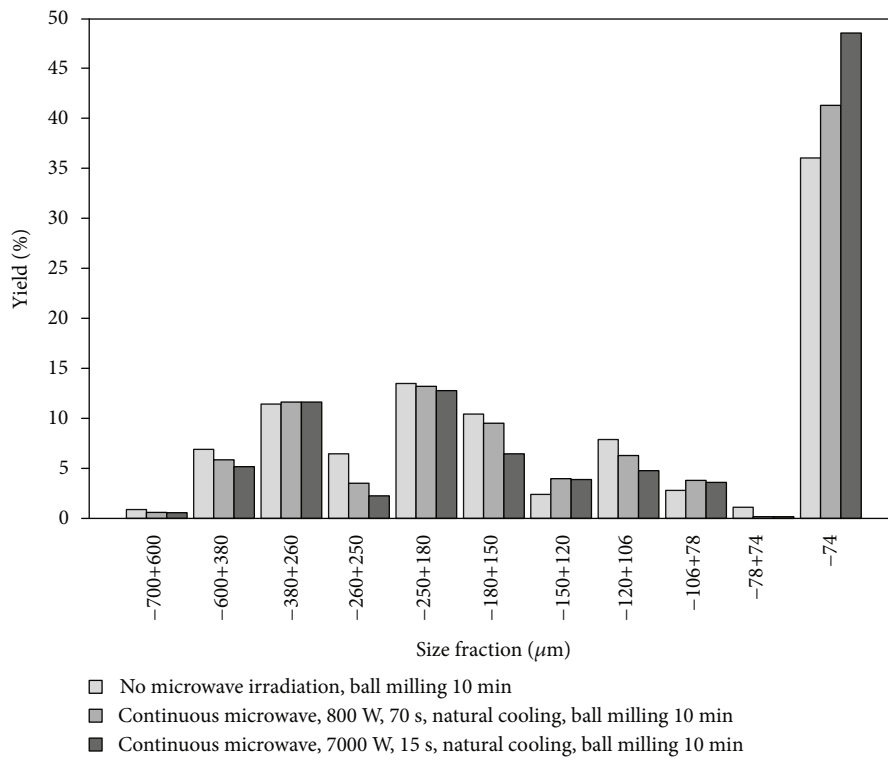


FIGURE 4: Effect of continuous microwave pretreatment on size fraction distribution of grinding products for lead-zinc ore.

water quenching can improve grinding better than natural cooling. When the lead-zinc ore was irradiated by pulsed microwave with power of 7kW for 15 seconds, the yields of the coarse fraction (260-380 μm) with water quenching decreased from 11.54% to 10.59% compared with natural cooling, and the yields of fine fraction below 0.074 mm increased from 49.58% to 52.71%.

3.4. Analysis and Comparison between the Effect of Continuous Microwave and Pulsed Microwave on the Particle Size of Grinding Products. Figure 10 showed the comparison diagrams of size fraction distribution of grinding products under different cooling methods with continuous and pulsed microwave pretreatment. It can be seen from

Figure 10 that the grinding effect after pulsed microwave pretreatment was better than that of continuous microwave pretreatment in both natural cooling and water quenching, and the percentage composition of coarse and medium size fraction is less than that by continuous microwave pretreatment. The content of fine fraction below 0.074 mm after pulsed microwave pretreatment was all larger than that by continuous microwave pretreatment, which increased by 0.97% under natural cooling and increased by 1.25% under water quenching.

In summary, the grindability of the ore after pulsed microwave pretreatment was improved compared with continuous microwave pretreatment under the same microwave power and irradiation time. The yields of size fraction below

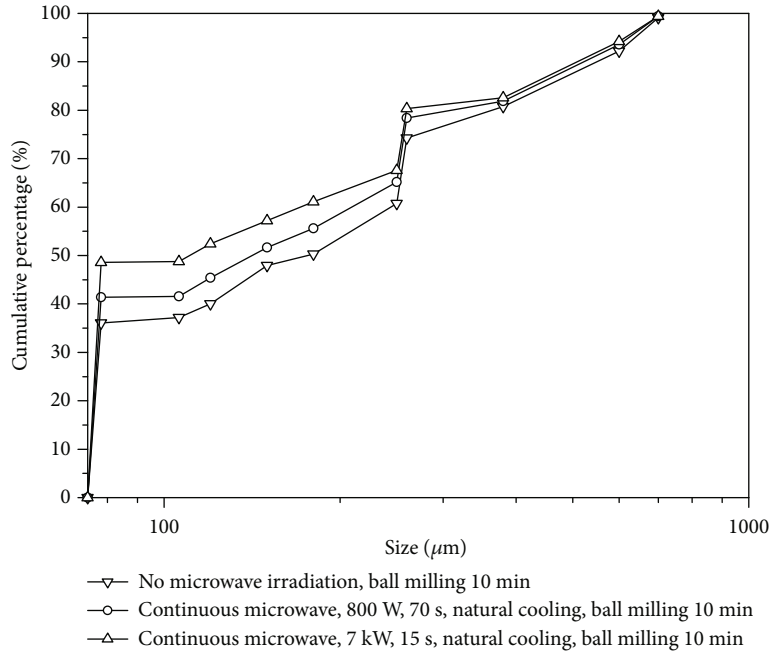


FIGURE 5: Effect of continuous microwave pretreatment on the particle size cumulative percentage of grinding products for lead-zinc ore.

0.074 mm increased at different degrees. It produced hysteresis phenomenon of rebound deformation because of the thermal stress formed by pulsed microwave pretreatment loads and unloads. And it caused irreparable residual deformation in the ore. The fatigue failure occurred in the ore promoted the grinding of lead-zinc ore as the circulation of load and unload increased. Therefore, the effect of pulsed microwave pretreatment on the grinding of lead-zinc ore was improved compared with continuous microwave pretreatment.

3.5. Effect of Microwave Pretreatment on Grinding Fineness. The lead-zinc ore was pretreated by microwave under different conditions, and then, it was milled for 10 minutes by planetary ball mill. Finally, the grinding fineness under different microwave pretreatment conditions was achieved by comparing and analyzing the yields of below 0.074 mm.

It can be seen from Figure 9 that the particle size yield of below 0.074 mm was 36.08% after grinding without microwave irradiation. When the continuous microwave irradiation was applied for 70 seconds with power of 800 W, the particle size yield of grinding products below 0.074 mm after natural cooling was 41.38%, improved by 5.30% compared with the untreated. The grinding fineness of the samples with pulsed microwave pretreatment was also higher than that with continuous microwave pretreatment under the same condition. This indicated that the lead-zinc ore pretreated by pulsed microwave could save more energy and improve the grinding fineness of the samples. For example, the particle size yield of grinding products below 0.074 mm was 52.71% after water quenching when the pulsed microwave was 7 kW and the irradiation duration was 15 seconds. This was higher than that with continuous microwave pretreatment under the same condition. And it was improved by

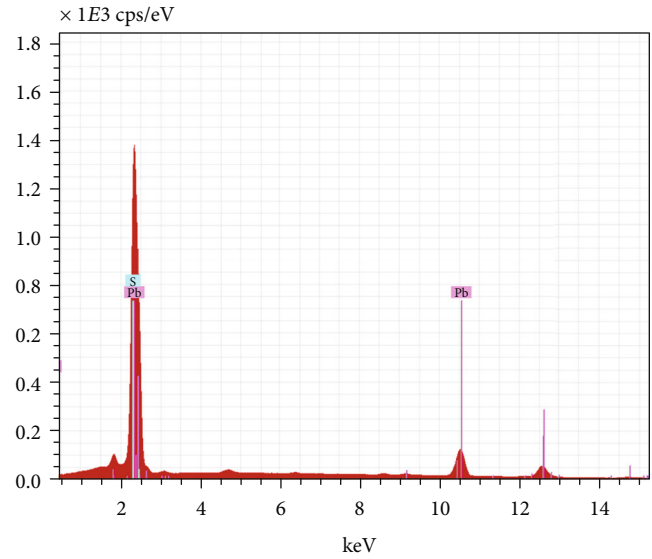
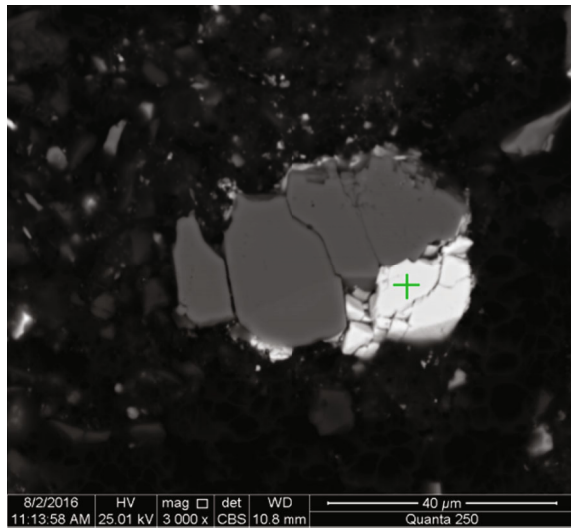
16.63% compared with the untreated, improving the grinding fineness of lead-zinc ore greatly.

3.6. Effect of Microwave Pretreatment on Energy Consumption of Grinding. In order to compare and analyze the energy consumption of grinding for lead-zinc ore under different microwave pretreatment conditions, the target grinding fineness which the yield of below 0.074 mm was set as 50%. According to the results of grinding tests, the ball milling time before reaching the target fineness and the energy consumption of grinding, under different microwave pretreatment conditions, was determined and calculated. Under the condition of the same grinding fineness, the energy consumption of the ore samples without microwave irradiation (E_1) mainly comes from the ball mill, and the calculation formula is shown in Eq. (1). The energy consumption of the samples pretreated by microwave (E_2) was mainly composed of the energy consumption of the ball mill during grinding (E_0) and the energy consumption generated during microwave pretreatment (E_m). It was calculated by Eq. (2).

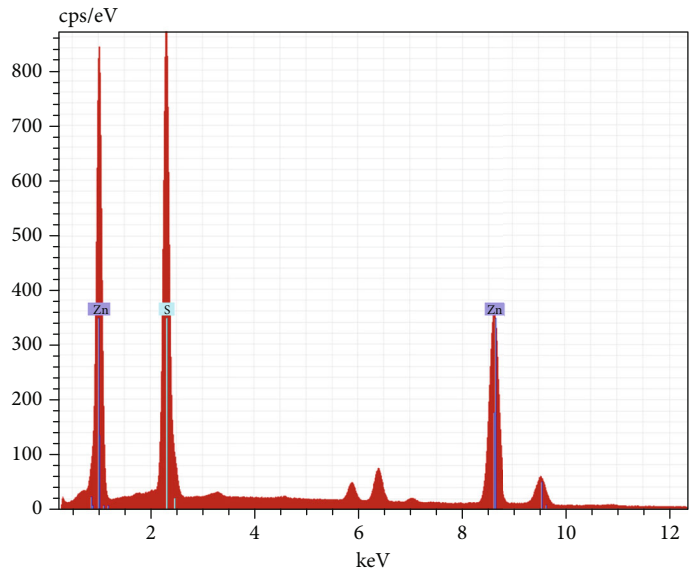
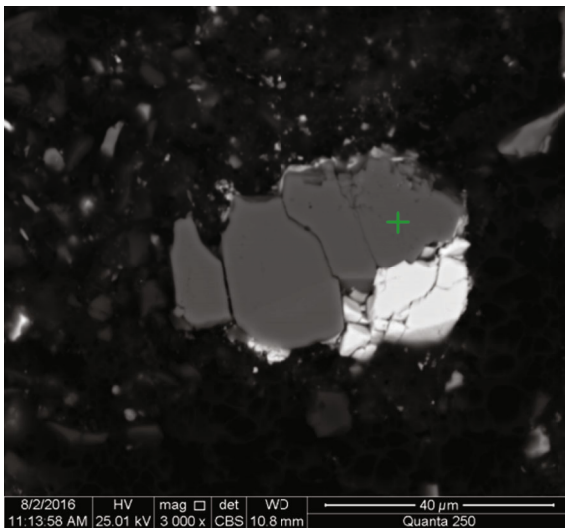
$$E_1 = P_1 t_1, \quad (1)$$

$$E_2 = E_0 + E_m = P_1 t_2 + P_2 \tau \frac{Q}{q}. \quad (2)$$

In Eq. (1) and Eq. (2), P_1 was the power of ball mill (kW), t_1 was the grinding time reaching the target fineness without microwave pretreatment (hour), t_2 was the grinding time reaching the target fineness with microwave pretreatment (hour), P_2 was the power of microwave (kW), τ was time of the microwave pretreatment (hour), Q was the give ore amount of ball mill, which were both 0.8 kg, and q was the



(a)



(b)

FIGURE 6: SEM and EDS images of lead-zinc ore after continuous microwave pretreatment.

weight of ore samples with microwave pretreatment, which were both 1 kg.

The grinding fineness of lead-zinc ore with different grinding time under different microwave irradiation process was shown in Table 3.

Figure 11 showed the influence of different ball milling time on the grinding fineness of lead-zinc ore after microwave pretreatment. It can be seen from Figure 11 that the yields of below 0.074 mm increased gradually with the increase of grinding time. The ball milling time for reaching the target fineness without microwave pretreatment was 15 minutes. When the power of continuous microwave was 800 W and the irradiation time was 70 seconds, the ball milling time for reaching the target fineness was 13 minutes, saving 2 minutes compared with that without microwave

pretreatment. The ball grinding time to reach the target grinding fineness was 12 minutes and 10 minutes, respectively, with continuous microwave pretreatment and pulsed microwave pretreatment when the power of microwave was 7 kW and the irradiation time was 15 seconds, which were 3 minutes and 5 minutes shorter than that without microwave pretreatment.

It suggested the grinding time of lead-zinc ore after microwave pretreatment was greatly shortened when the same target fineness was achieved compared with that without microwave irradiation, and the energy consumption of grinding was also saved when the grinding efficiency was improved.

In the laboratory condition, 1.0 kg of ore samples was pretreated by microwave each time. The give ore amount of

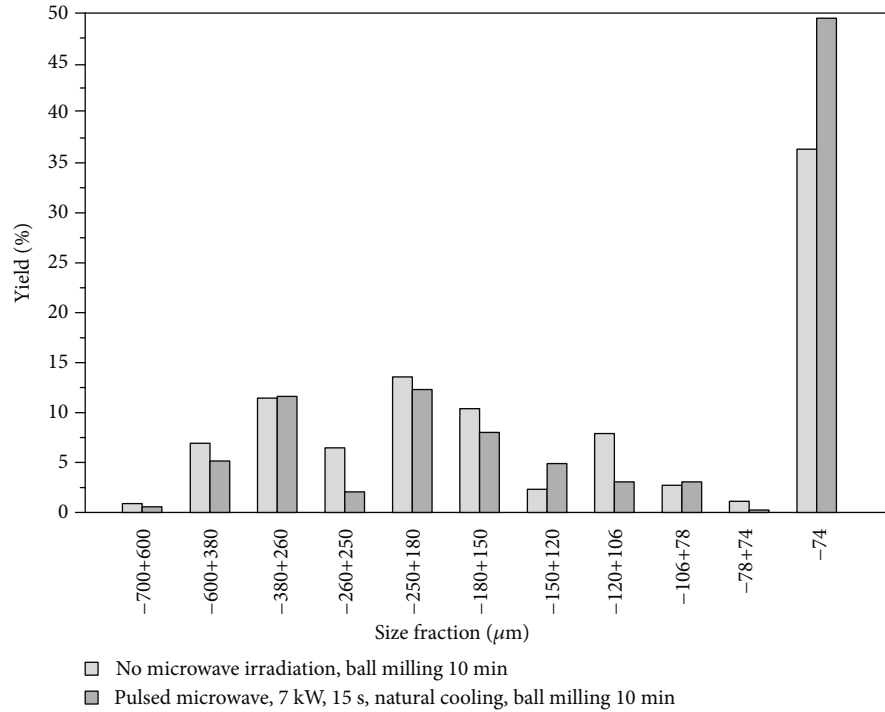


FIGURE 7: Effect of pulsed microwave pretreatment on size fraction distribution of grinding products for lead-zinc ore.

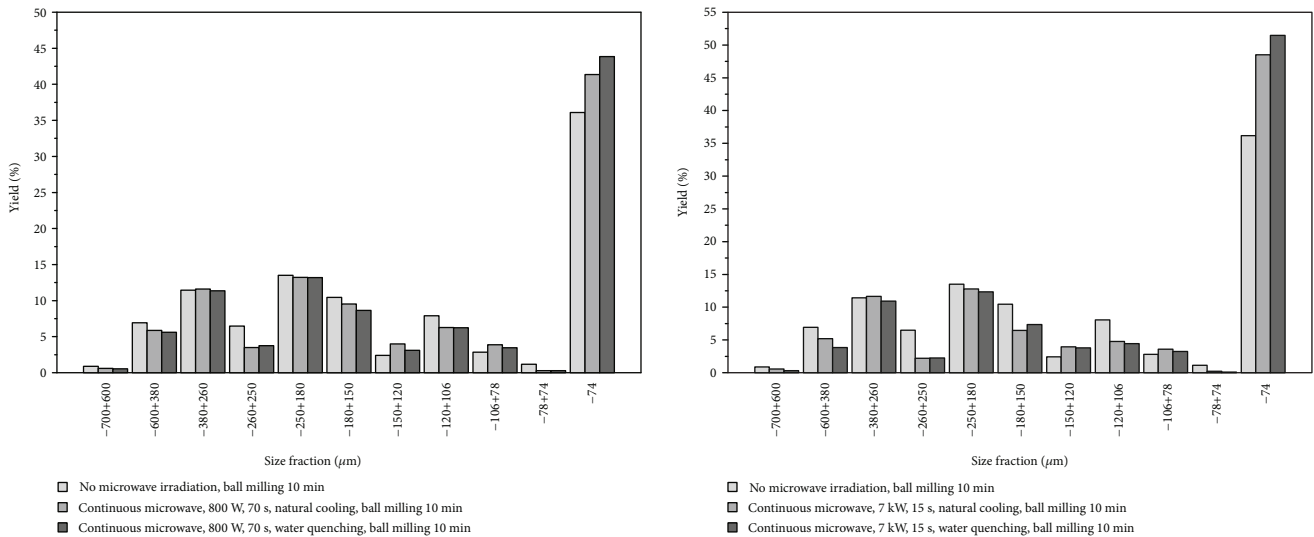


FIGURE 8: Effect of cooling method on the size fraction distribution of grinding products after continuous microwave pretreatment.

each ball grinding was 800 g, and the power of the ball mill was 2.2 kW. The calculation results of energy consumption and the total energy consumption distribution of reaching the target grinding fineness for lead-zinc ore under different microwave pretreatment conditions were shown in Figure 12.

It can be seen from Figure 12 that the energy consumption of lead-zinc samples without microwave irradiation was 0.55 kW·h when the target grinding fineness was reached. When the power of continuous microwave was

800 W and the irradiation time was 70 seconds, the total energy consumption of reaching the target grinding fineness was reduced to 0.49 kW·h, in which the energy consumption of microwave pretreatment was 0.01 kW·h and the energy consumption of grinding was 0.48 kW·h. In addition, the total energy consumption was reduced by 10.9% compared to that without microwave irradiation. The microwave pretreatment could reduce the comprehensive energy consumption of grinding process for the lead-zinc ore obviously. When the power of continuous microwave was 7 kW and the

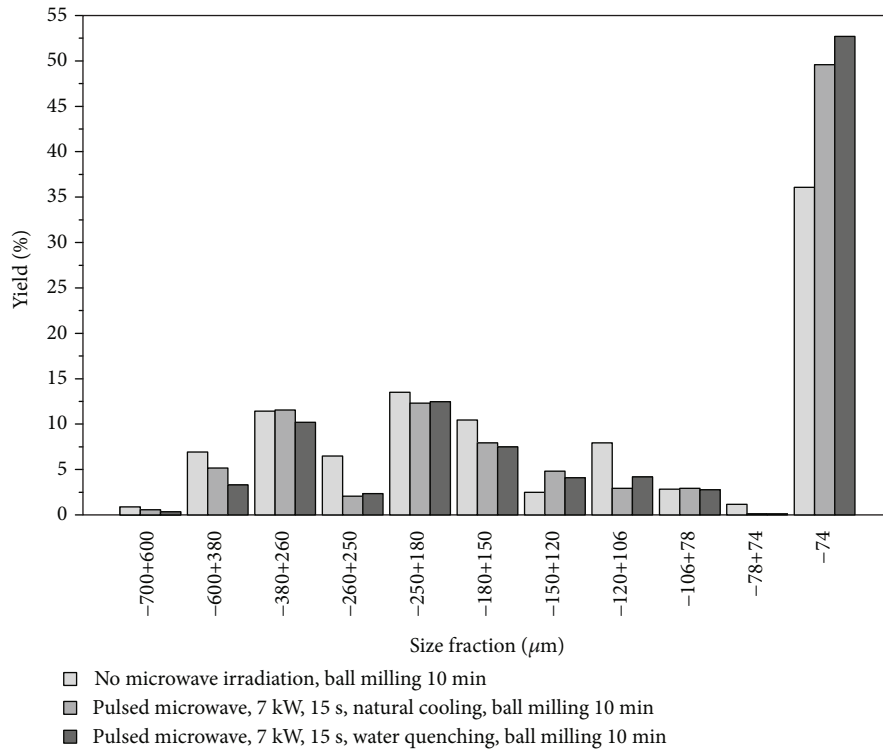


FIGURE 9: Effect of cooling method on size fraction distribution of grinding products after pulsed microwave pretreatment.

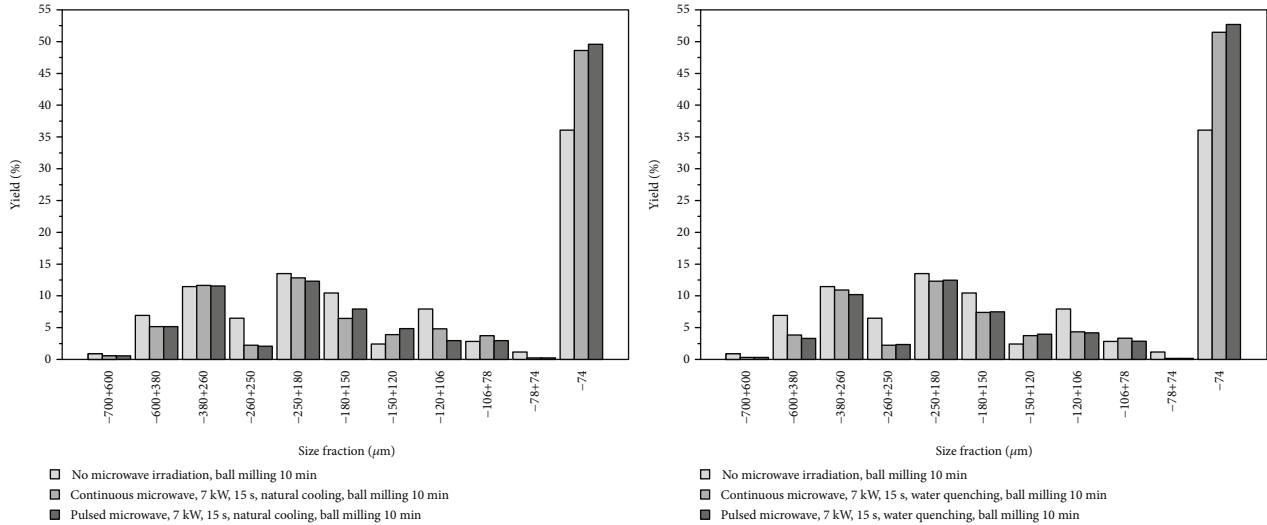


FIGURE 10: Comparison diagrams of the size fraction distribution of grinding products under natural cooling and water quenching after continuous and pulsed microwave pretreatment.

irradiation time was 15 seconds, the total energy consumption was 0.46kW·h, which was 16.4% lower than that without microwave irradiation. It showed that the comprehensive energy consumption decreased more obviously with the increase of power of continuous microwave. When the power of pulsed microwave was 7kW and the irradiation time was 15 seconds, the total energy consumption of reaching the target grinding fineness was only

0.38kW·h. It was 30.1% lower than that without microwave irradiation, and the energy consumption decreased the most. Pulsed microwave pretreatment was more effective in reducing the comprehensive energy consumption of grinding process of lead-zinc ore compared with continuous microwave pretreatment.

In conclusion, under the condition of achieving the same target grinding fineness, the energy consumption of grinding

TABLE 3: Grinding fineness of lead-zinc ore with different grinding time under different microwave pretreatment conditions.

Pretreatment conditions	Pretreatment time τ (s)	Grinding time t (min)	Give ore amount Q (kg)	The yields of below 0.074 mm (%)
No microwave irradiation	0	10	0.8	37.80
	0	11	0.8	40.04
	0	12	0.8	42.88
	0	13	0.8	45.31
	0	14	0.8	47.80
	0	15	0.8	50.23
Continuous microwave, power of microwave was 800 W, natural cooling	70	10	0.8	42.03
	70	11	0.8	43.99
	70	12	0.8	46.27
	70	13	0.8	49.84
	70	14	0.8	51.07
Continuous microwave, power of microwave was 7 kW, natural cooling	15	10	0.8	46.55
	15	11	0.8	48.13
	15	12	0.8	49.87
Pulsed microwave, power of microwave was 7 kW, pulse width was 1 ms, working frequency was 500 Hz, natural cooling	15	13	0.8	51.34
	15	10	0.8	49.53
	15	11	0.8	52.38

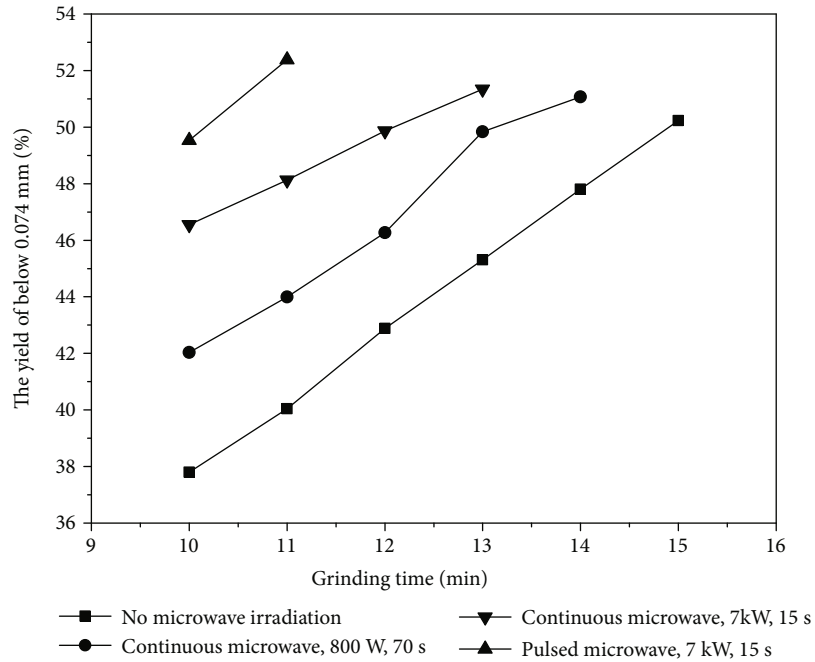


FIGURE 11: The influence of ball milling time on the grinding fineness of lead-zinc ore after microwave pretreatment.

for the lead-zinc ore samples without microwave pretreatment was greater than the sum of the energy consumption of microwave pretreatment and the energy consumption of ball milling. It indicated that the microwave pretreatment could assist in grinding and reducing energy consumption in the process of lead-zinc ore.

4. Conclusions

The pretreatment of lead-zinc ore with different microwave parameters was carried out. The conclusion can be reached as the following by analyzing the changes of particle size distribution, energy consumption of grinding, and the yields of

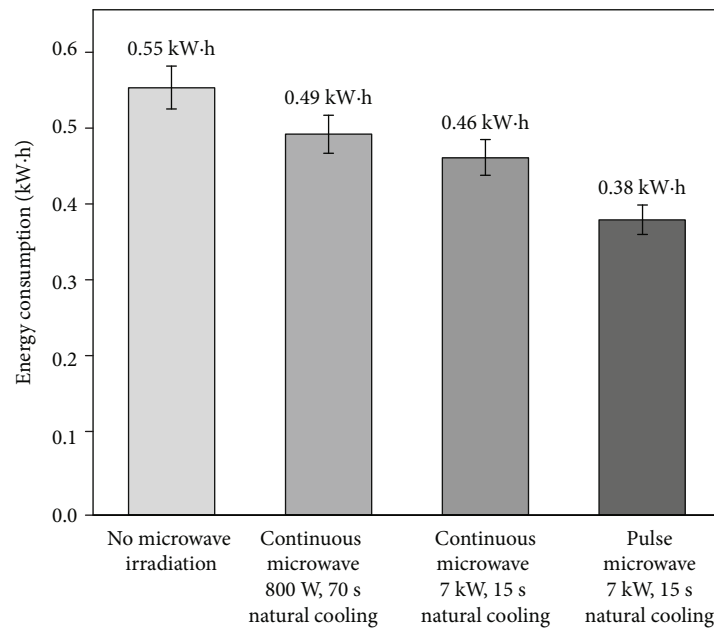


FIGURE 12: The total energy consumption of reaching the target fineness for lead-zinc ore under different microwave pretreatment conditions.

grinding products below 0.074 mm before and after microwave pretreatment.

- (1) Continuous microwave pretreatment could improve the grinding efficiency of lead-zinc ore, and the particle size of grinding products became finer with the increase of microwave power. The yield of grinding products below 0.074 mm was 36.08% without microwave irradiation. When the power of continuous microwave was 800 W and the irradiation time was 70 seconds, the yield of grinding products below 0.074 mm after natural cooling was 41.36%, which was 5.28% higher than that of untreated. And the particle size distribution curve of grinding products was obviously above that without microwave irradiation. This was because the lead-zinc minerals were easy to absorb microwave energy and converted the energy into thermal energy under microwave irradiation, while the gangue minerals were not easy to absorb microwave energy. Then, thermal stress was formed in the ore due to the temperature gradient, which led to microcracks along the grain boundary of minerals, reduced the mechanical strength of the ore, and improved the grinding effect
- (2) In summary, the grindability of the ore after pulsed microwave pretreatment was improved compared with continuous microwave pretreatment under the same microwave power and irradiation time. The yield of size fraction below 0.074 mm increased in certain degree. It produced hysteresis phenomenon of rebound deformation because of the thermal stress formed by pulsed microwave pretreatment loads and

unloads. And it caused irreparable residual deformation in the ore. The fatigue failure occurred in the ore which promoted the grinding of lead-zinc ore as the times of load and unload increased. Therefore, the effect of pulsed microwave pretreatment on the grinding of lead-zinc ore was improved compared with continuous microwave pretreatment

- (3) The effect of water quenching on the grinding of lead-zinc ore was more remarkable than that of natural cooling whether it was pretreated by continuous microwave or pulse microwave. It was because that the water quenching can prevent healing microcracks formed along the mineral grains' boundaries due to thermal stress generated by microwave irradiation. At the same time, water quenching also causes a sudden drop in temperature in and outside the ore, which further expands the original grain boundary cracks of the minerals inside the ore
- (4) Under the condition of achieving the same target grinding fineness, the energy consumption of grinding for the lead-zinc ore samples without microwave pretreatment was greater than the sum of the energy consumption of microwave pretreatment and the energy consumption of ball milling. When the power of continuous microwave was 800 W and the irradiation time was 70 seconds, the total energy consumption of reaching the target grinding fineness was reduced to 0.49 kW·h, which was reduced by 10.9% relative to that without microwave irradiation. When the power of continuous microwave was 7 kW and the irradiation time was 15 seconds, the total energy consumption was 0.46 kW·h, which was 16.4% lower

than that without microwave irradiation. When the power of pulsed microwave was 7 kW and the irradiation time was 15 seconds, the total energy consumption of reaching the target grinding fineness was only 0.38 kW·h. It was 30.1% lower than that without microwave irradiation, and the energy consumption decreased the most. Pulsed microwave pretreatment was more effective in reducing the comprehensive energy consumption of grinding process of lead-zinc ore compared with continuous microwave pretreatment

Data Availability

All data used in this study can be obtained by contacting the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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