Effects of microwave irradiation on impact comminution and energy absorption of magnetite ore

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Abstract. The severe mechanical wear and high-energy consumption in the comminution process of high hardness iron ore have always restricted the efficient and economic development of an enterprise. On the basis of the basic principle that microwave irradiation can induce rock damage, the magnetic ore specimens were subjected to microwave heating treatment with different heating paths and cooling paths; the uniaxial impact comminution test was conducted by the drop hammer impact equipment. This study analyzed the effect of the heating and cooling paths on the crack propagation process, dynamic mechanical strength, and energy consumption of magnetite ore. The results show that microwave irradiation causes obvious microwave-induced cracks in ore, and in the subsequent impact cracking process, the new cracks gradually penetrate the microwave-induced cracks and form the macroscopic fracture surface. With the increase of irradiation power and time, the ore dynamic strength decreased, and the absorption energy increased. Therefore, increasing the total output energy of microwave can effectively alleviate the mechanical wear and enhance the comminution effect of ores. Among the factors that affect the mechanical properties and absorption energy of ore, power has a higher priority than time. With the increase in the heat exchange rate between the ore and the external environment, the ore comminution becomes more intense, leading to the best comminution effect of ores. The research results have an important reference for the practical application of microwave irradiation technology in hard rock comminution.

1. Introduction
In the field of mining and mineral processing, breaking high hardness rock economically and effectively has always been the focus of engineering science. Traditional methods of breaking hard rock include drilling and blasting method and mechanical rock breaking method (tunnel boring machine). The drilling and blasting method is suitable for breaking large ore rock, but not for the ore comminution in concentrating mill; moreover, this method can easily cause irreversible blasting vibration damage to nearby underground projects. The principle of rock comminution equipment widely used in concentrating mill is mechanical rock breaking, which has strong applicability, but it will produce serious tool wear problems and reduce the comminution efficiency with the crashing process. The electricity consumption of the ore comminution process in concentrating mill accounts...
for approximately 5% of the total electricity consumption of the world, whereas the energy utilization for generating a new section of ore is only 1% (Jones et al. 2007), indicating considerable energy waste in the process of ore comminution. Thus, it is urgent to find a new rock comminution technology on the basis of traditional comminution technology for high hardness rock (Peinsitt et al. 2010).

The technology of microwave heating has the advantages of fast heating rate, uniform temperature, and high efficiency, thus leading to increased utilization in various industries. As has been preliminarily explored in tunneling and drilling of hard rock, microwave irradiation can rapidly heat the rock, generate thermal stress concentration inside the rock, and weaken the mechanical properties of the rock (Jerby et al. 2012; Hassani et al. 2016). At present, in the microwave cracking mechanism, by using numerical simulation method, researchers have carried out valuable studies on mineral expansion under microwave irradiation (Whittles et al. 2003), selection of microwave types (Jones et al. 2005), scattering distribution of the electromagnetic field (Hassani et al. 2016), sensitivity analysis of minerals to microwave (Li et al. 2019), and other aspects. In the microwave effect on the physical properties of rocks, Hartlieb et al. (2016; 2018) pointed out that the difference in quartz content and water content leads to the difference in the ability of rocks to absorb microwaves. Shepel et al. (2018) also indicated that there exists a threshold value of irradiation time when the granite was irradiated. Zheng et al. (2017) observed the propagation process of radial cracks in rocks under microwave irradiation by using self-designed experiments. Previous studies also analyzed the effects of microwave power and irradiation time on the P-wave velocity and uniaxial compressive strength of hard rock from multiple angles (Nicco et al. 2018; Lu et al. 2019; Lu et al. 2019).

Kingman et al. (2000) early proposed the method of microwave pre-treatment before ore comminution to apply microwave irradiation to the ore comminution process in concentrating mill. Lovás et al. (2003) found that microwaves could improve the recovery rate of silver metal in copper ore. On the basis of the microwave irradiation test of titanium iron ore, Zhao et al. (2014) pointed out that microwave irradiation can be used to reduce the energy consumption of ore comminution. In addition, the research on microwave irradiation has made some progress in the separation of various minerals and removal of impurities in minerals (Waters et al. 2007; Liu et al. 2015; Elmahdy et al. 2016; Farahat et al. 2017). However, in the currently published results, there are few targeted research results on the comminution characteristics and energy absorption of high hardness ores by microwave irradiation. Therefore, this study first conducted microwave pre-treatment of magnetite ore with different heating and cooling paths and then studied the effects of the heating and cooling paths on the strength, failure process, and absorption energy of the ore through the drop hammer comminution test. This paper can provide a reference for the application of microwave irradiation technology in the future hard rock comminution process.

2. Test process

2.1. Microwave treatment of magnetite ore

The magnetite blocks collected from the mine were processed into 50 mm × 50 mm × 100 mm cuboid specimens. The microwave heating test of the magnetite ore specimens was carried out by RWLM6 high-temperature microwave muff furnace. To study the effect of the heating path on the subsequent ore comminution, we pre-treated a group of specimens with the same power and different irradiation time (MPO group); the other group of specimens was pre-treated with the same irradiation time but different heat power (MBT group). After the heating process is completed, the above specimens were cooled to room temperature. To study the effect of the cooling path on the subsequent ore comminution, we first heated some specimens with a power of 2 kW and 5-min irradiation, and then they were cooled down in different conditions, which is natural cooling down at room temperature, and cooling down by water spray and water impact (MCL group). At the same time, we selected three samples without microwave irradiation as the control group.

Table 1. Microwave irradiation groups of magnetic ore
| Group | Power (kW) | Time (min) | Cooling path                      |
|-------|------------|------------|-----------------------------------|
| MPO   | 2.0        | 3.0/5.0/7.0| Room temperature (25°C)           |
| MBT   | 1.2/2.0/2.8| 5.0        | Room temperature (25°C)           |
| MCL   | 2.0        | 5.0        | Room temperature (25°C), spray water, water impact |

2.2. Drop hammer impact comminution test

In the process of comminution ore in actual mining plant and concentrating mill, the ore blocks are subjected to mechanical impact load by jaw crusher and other equipment to break it into small pieces. The force on ores is approximately the uniaxial impact load in the process of comminution ore. This study used the DP-1200 drop hammer impact device to conduct impact comminution test on the above magnetic ore specimens, with a stroke height (H) of 1000 mm and a hammer weight (M) of 50 kg. The ore comminution process was recorded by FASTEC-TS3 high-speed camera with 450 frames per second (Fig. 1). To obtain more precise failure details of the specimens, we uniformly sprayed the cooled specimen surfaces with white paint to remove the black and brown colors on the rock surface. In the impact test of three groups of ores with microwave irradiation, three samples were selected for the same conditions. For example, in the MPO group, when the power is 2 kW and the time is 3 min, three specimens were selected.

![Figure 1. Impact comminution of magnetite ore](image)

2.3. Calculation of energy

In the impact experiment, the hammer head freely falls from a predetermined height to strike the specimens, and the upper end of specimens is subjected to strong mechanical impact to form stress waves. The ore specimen dissipates part of the energy carried by the stress wave, and the buffer device absorbs the rest of the energy at the pedestal. In the beginning, the total energy $W$ is converted into the dissipated energy $L$ and the transmitted energy $T$ absorbed by the pedestal. The transmitted energy $W_t$ can be obtained through the data acquisition device of the pedestal. The potential rebound energy of the hammer head can be neglected because of the anti-secondary impact device in the drop hammer system. $W_t$ is mainly composed of the absorption energy $W_h$ and the kinetic energy $W_k$ of ore fragments. According to early studies, the proportion of rock absorption energy $W_h$ in $W_t$ is higher than 85%, and the proportion of debris kinetic energy $W_k$ in $W_t$ is lower than 8% (Zhang et al.
2000). Therefore, this study considers the absorption energy $W_a$ approximately as the ore dissipated energy $W_L$. The relevant energy is calculated as follows.

\[ W=W_{mgh} \]  
\[ W=W_L + W_t \]  
\[ W_L=W_{mgh} + W_k \approx W_{tt} \]

(1) \hspace{1cm} (2) \hspace{1cm} (3)

where $m$ is the weight of the drop hammer (kg), $h$ is the impact height (m), and $g = 9.8 \text{m/s}^2$.

To characterize the ratio of ore dissipated energy $W_L$ to the total energy $W$, we introduce the energy utilization rate $\eta$.

\[ \eta = \frac{W_L}{W} \]  

(4)

3. Analysis of test results

3.1 Effect of microwave irradiation on ore strength

To reflect the weakening law of microwave irradiation on the ore dynamic strength more intuitively, we used the strength ratio of ore before and after microwave irradiation. It is the decay law of the dynamic strength of each specimen (Fig. 2). When the microwave irradiation power is the same, the ore dynamic strength decreased from 76.38% to 51.64% with the irradiation time from 3 to 5 min. When the irradiation time is the same, the ore dynamic strength decreased from 79.15% to 43.21% with the increase of irradiated power from 1.2 to 2.8 kW. Comparing the data between the MPO group and MBT group, it can be seen that when the total microwave output energy ($W = P \cdot T$) is the same, the reduction of ore strength is the largest after high-power microwave irradiation. Among the factors affecting the dynamic strength of ore, microwave power has a higher priority than irradiation time.

In the MCL group, the surface of the ore under high temperature experiences intense expansion and contraction state after encountering water. Under normal temperature (25°C) and pressure conditions ($1 \times 10^5 \text{Pa}$), because the specific heat capacity of water is approximately four times that of air, the cooling rate of ore cooled at room temperature is lesser than that of ore under water environment. Therefore, after the ore under high temperature conditions encounters water, the temperature of the ore decreases rapidly because of strong thermal expansion and contraction. More new cracks are generated on the surface of the ore, which aggravates ore damage. The liquid water invading the inner ore is vaporized and expanded after heating, and the water vapor further aggravates the damage inside the ore. Under the same microwave power and the same irradiation time, the ore cooled by water impact has the greatest reduction of strength. It shows that increasing the heat exchange rate between ore in high temperature and the surrounding environment can significantly weaken the ability of ore to resist external load (strength).
3.2. Process of ore fracture

Figure 3 shows the ore fracture process after microwave heating (2 kW, 5 min), followed by natural cooling at room temperature. The direction of some microwave-induced cracks in the specimen is parallel to the horizontal direction. The stress distribution and transmission process extend to the middle of the specimen along the direction of the maximum principal stress (the end of the specimen), and the new cracks will break through the microwave-induced cracks. In the initial stage of failure, small tensile cracks are first generated at the loading end and then further develop and propagate towards the middle of the specimen. As the impact load continues to be applied, tensile cracks gradually expand and converge, leading to the failure of the magnetite ore.

Figure 4 shows the ore fracture process after microwave heating (2 kW, 5 min) and water spray cooling. The ore cooled by water has a high degree of internal damage; this is reflected by the rapid development of tensile cracks from the end to the middle of the specimen at the initial stage of failure. Tension-shear mixed cracks gradually appear as the advent of shear cracks along with the tensile stress. Therefore, a large number of new cracks break through the microwave-induced cracks under tensile stress, and cracks of different scales and anisotropy coalesce and cut through the specimen.
3.3. Effect of microwave irradiation on absorption energy

Figure 5 shows the changes of the absorption energy. Part of the kinetic energy of the hammer is converted into the energy required for ore crushing. The energy utilization rate of specimens in three groups is also shown in the figure. With the increase of the total microwave output energy, the absorption energy and energy utilization rate of magnetite ore increase under the same impact condition. When the output energy of microwaves is the same, the increase of microwave power can enhance the ability of ore to absorb external load energy. Among the factors affecting the absorption energy of ore, microwave power has a higher priority than the irradiation time. In the MCL group, increasing the heat exchange rate between the ore and the surrounding environment can improve the absorption energy. The rapid cooling method of water impact can improve energy utilization in the process of comminution ore, thereby increasing the efficiency of comminution ore.

Microwave irradiation causes unequal thermal expansion within the ore and causes microwave-induced cracks inside the ore because of the difference in mineral composition, which increases the damage of the ore and reduces the wave impedance. To increase the total microwave output energy (at the irradiation stage) or the heat exchange rate (at the cooling stage), the transmitted energy reaching the drop hammer pedestal reduces because of the decrease in the wave impedance of ore. In this study, the absorption energy increases because of the decrease in wave impedance. This is similar to the energy transmittance of coal rock materials with low wave impedance is lower than that of hard rock materials with high wave impedance in the Split Hopkinson Pressure Bar impact test (Gong et al. 2018; Chen et al. 2018).
4. Conclusions
The microwave heating method can weaken the dynamic strength and increase the absorption energy of the ore, thereby increasing the efficiency of comminution ore. Under the drop hammer impact load, the ore after microwave irradiation starts to crack at the end, and then the cracks develop toward the middle of the ore and break the microwave-induced cracks. Our results show how to maximize the damage in ore and minimize the total microwave output energy. Increasing microwave power takes advantage of extending the irradiation time. After the microwave irradiation is completed, compared with the ore cooled at room temperature (25°C of air), the ore is subjected to more intense thermal expansion and contraction when cooling with water, and the water vapor in the ore cracks causes the ore to produce more cracks. Compared with the water spray method, the water impact method can increase the heat exchange rate between the ore and the external environment and can significantly increase the energy utilization rate in the comminution process, thus leading to lower production cost.
5. References

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