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The effect of energies on the impact breakage characteristic of magnetite ores

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Abstract: The energy applied during breakage is the key to enhancing the magnetite liberation degree and improving quality. The relationship between energy and liberation properties remains unclear due to various complicated factors affecting mineral liberation. Therefore, this work aims to study the effect of energy on the breakage characteristics of magnetite ores; the impact breakage test was conducted on magnetite particle groups at different energies using a drop weight impact tester; the statistical analysis was performed based on the fractal theory to research the particle size distribution; the fracture morphology and liberation properties of these ores were analyzed using scanning electron microscope and mineral liberation analyzer. Results show that the particle size distribution of magnetite after breakage conforms to the fractal law. The larger the energy, the greater the fractal dimension for this distribution, showing a linear relation between them, which implies that the fractal dimension can evaluate the breakage degree. The fracture morphology of magnetite ores indicates that as the energy increases, the intergranular fracture evolves into transgranular fracture, proving the influence of energy on fracture modes. It is found that the magnetite liberation degree first increases and then decreases with the rising of energy, indicating that the magnetite liberation can be improved at an appropriate amount of energy. The above conclusions provide a theoretical reference for optimizing energy and improving broken product quality.

***Keywords*:** fractal dimension, ore breakage characteristic, particle size distribution, minerals liberation, fracture morphology

1. Introduction

The grinding process mainly seeks to minerals liberation and reduce their particle size, and the process requires high energy consumption. For example, the power consumed for ore grinding accounts approximately 40~50% of the overall power consumption and 2% of the gross generation in China. In contrast, the effective energy consumed in this process only accounts for 3~8% of the input energy (Zeng et al., 1991). Therefore, it is important to optimize the ore grinding and reduce energy consumption by studying ore breakage characteristics.

Particles are broken in two modes: single particle breakage and particle group breakage. Numerous studies have been conducted on the breakage characteristics of particles (Yu et al., 2018). Grouped breakage is more complicated, with energy transfer between particles. Particle group breakage is affected by various factors. For instance, the energy needed for this process is closely related to the layer thickness and particle size of the particle group (Han et al., 2006; Danha et al., 2016).

There has been extensive research exploring the relationship between energy and the particle size distribution of comminution products. Fuerstenau et al. (1996) concluded from their tests on these two modes that the breakage was primarily caused by crack propagation, and the energy consumed in this process was associated with particle size. Jiang et al. (2021) studied the characteristics of particle group breakage through a compression test, based on which they set up a relational expression between the energy and particle size and proposed a characteristic index for this size to predict the law of particle size reduction. Benjamin et al. (2017) verified the significant difference in the particle size distribution

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of products from particle group breakage and single particle breakage according to the results of a drop ball impact test.

Considering the great influence of different breakage modes on liberation behaviors, the energy consumed for regulated and controlled according to the physicochemical properties of minerals. Wills et al. (1993) discussed the impact of crack propagation speed on intergranular and transgranular fractures under load and concluded that the former could be promoted by low energy consumption and low strain rate, which, to a certain extent, enhanced the magnetite liberation degree. Bradt et al. (1995) found the size effect of particle breakage and the critical value of particle size in intergranular fracture through a loading test on ore particles. Leißner et al. (2016) developed a new method to identify intergranular and transgranular cracks on the mineral surface and calculated the number of such exposed cracks before and after the particle breakage based on the specific surface area.

Study on the relationship between energy and minerals liberation is helpful in establishing particle breakage model. However, due to the complexity of mineral liberation, the relationship between energy and mineral liberation has not been established so far. Garcia et al. (2009) developed a mineral interface area measurement system by using X-CT reconstruction images to calculate the area ratio of different mineral interfaces before and after particle breakage, the results showed that minerals fracture mode at low energy is mainly intergranular fracture, which is conducive to minerals liberation. Fu et al. (2019) studied the coal breakage characteristics by using impact test system, mineral liberation analysis results show that under a certain range of energy applied, the interface fracture of different minerals will increase the minerals liberation. Mariano et al. (2018) studied the breakage tests on pyrites and copper sulfides at different energies using JKRBT, based on which they summarized that the applied energy had little impact on the distribution of minerals liberation degree. Si et al. (2021) carried out eight different single ball diameters of grinding test, and the results showed that large breakage energy generated by large ball diameter could undermine the minerals liberation. Under the appropriate ball diameter, the minerals liberation of the grinding product is higher, while over-crushing was also avoided.

Therefore, regulating the energy and breakage modes during ore grinding is extremely important to improve the liberation degree of comminution products. In this research, the impact breakage test was conducted on magnetite ores breakage using a drop weight impact tester to explore the effect of energy on particle size distribution, particle morphology, and liberation degree of the particle group magnetite after crushing, thus revealing the impact energy on breakage characteristics. This study provides theoretical and data supports for researching the comminution mechanism.

2. Materials and methods

2.1. The sample preparation

The magnetite ore used in this paper was taken from iron ore mining in Sishanling of Benxi, Liaoning Province. XRD analysis of the mineral phase composition of the sample is shown in Fig. 1. The results of X-ray diffraction analysis show that the strong peaks in the samples are magnetite and quartz, using stannous chloride reduction titration and silicon molybdenum blue colorimetry method, the results show that the magnetite and SiO2 are 45.00 % and 49.73 % respectively.

The mineral composition of magnetite ores was analyzed using the advanced mineral identification and characterization system (AMICS-Mining). To clearly distinguish the mineral components, they were marked in different colors, as presented in Fig. 2. Results show that magnetite ores are composed of the following minerals: magnetite, quartz, hornblende, calcite, apatite, etc., of which magnetite and quartz are mainly distributed. The species, area percentage, mass percentage, and the number of minerals contained on the surface in Fig. 2 were measured through the quantitative spectrum analysis with AMICS-Mining. The mass of magnetite, quartz, and hornblende accounts for 32.48%, 61.73%, and 4.56% in magnetite ores, respectively, higher than that of other components, which further verifies that these ores primarily consist of magnetite and quartz. In terms of occurrence state, the occurrence state of each mineral is quite different. In the area dominated by quartz distribution, magnetite and hornblende minerals are isolated and dispersed in the quartz matrix in its shape. The particle size is small, generally less than 0.050 mm. In the area where magnetite is distributed, the main gangue minerals are quartz and hornblende. Among them, quartz is distributed in magnetite with a large particle size, and hornblende is mainly distributed in a granular manner with a small particle size.

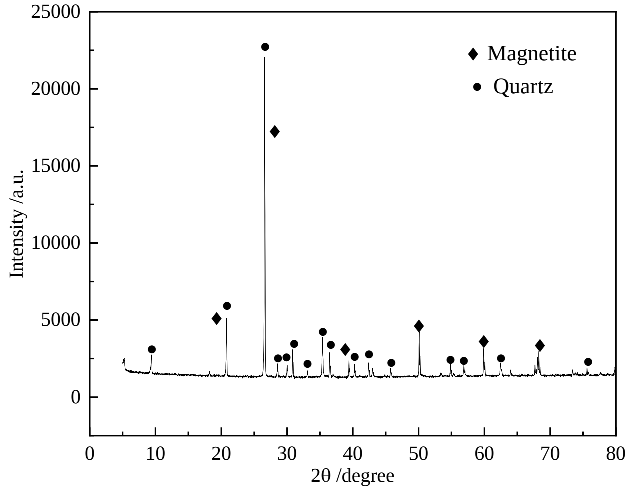

Fig. 1. XRD patterns of magnetite ore sample

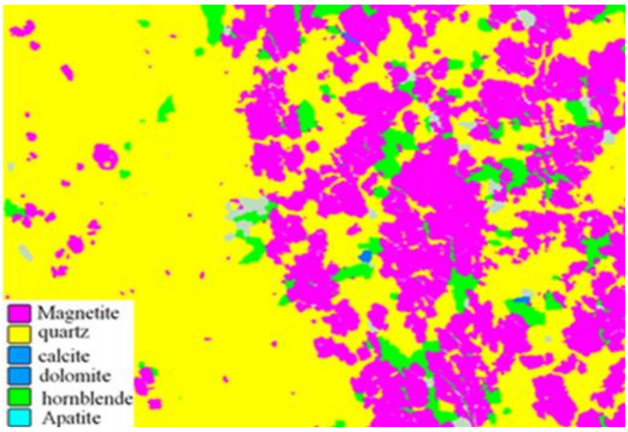

Fig. 2. AMICS-Mining image of the ore sample

2.2. The mechanics properties of magnetite and quartz

Magnetite ore samples are mainly two-phase minerals composed of quartz and magnetite. Quartz and magnetite show different color characteristics by the optical microscope, which can distinguish mineral components. The nanoindentation test of quartz and magnetite in magnetite ore under the same load is carried out to measure minerals microscopic mechanical parameters, as shown in Fig. 3.

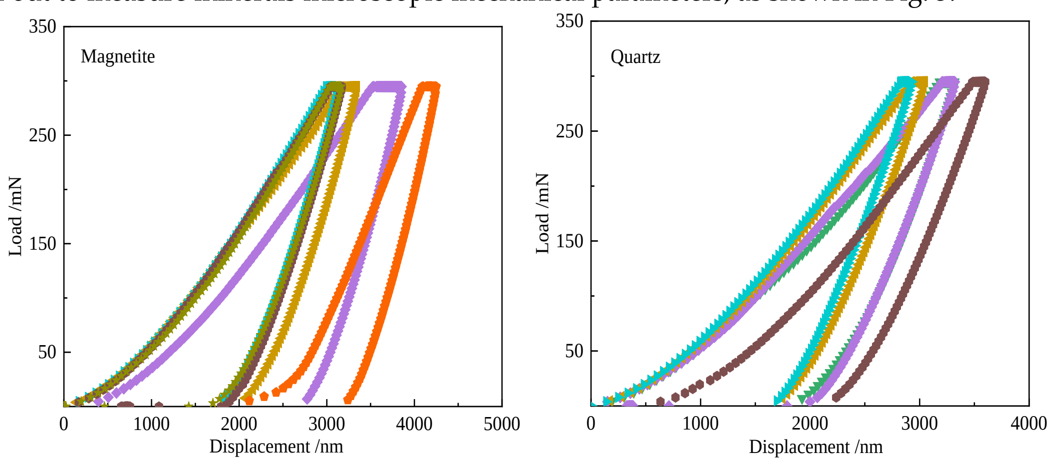

Fig. 3 Nanoindentation load-displacement curves

According to the Oliver-Pharr method, the micro-hardness and elastic modulus of the material can be obtained (Oliver et al,. 2004). It can be seen that the average hardness and elastic modulus of quartz are 2.00 Gpa and 22.28 GPa; the average hardness and elastic modulus of magnetite are 1.85 Gpa and 21.53 GPa, respectively. The difference in mechanical parameters of quartz and magnetite reflects the heterogeneity of magnetite ore; among them, magnetite is easy to be broken under the same stress.

2.3 Particle group ores impact breakage test

Fig. 4. Ore breakage test system;(a) drop weight impact equipment; (b) particles recovery unit; (c) particle group test tank

In the drop weight impact system (Fig. 4), an impact tester was elevated to different heights to breakage three kinds of ore samples at different energies, as shown by the equipment drawing in Fig. 4 (a). A holding tank was installed below the impact hammer to hold samples and collect comminution products, as presented in Fig. 4 (b). The tank used for the drop weight impact test on the particle group was exhibited in Fig. 4 (c).

The magnetite particles of -2.000+1.180 mm were selected to research the effect of layer thickness on particle group breakage. Thereinto, the magnetite ore weight of 100g, 150g and 200g are selected to represent the particle layer thickness of 0.83 cm, 1.45 cm and 1.82 cm respectively, which were used to test the particle breakage by different impact energies.

Fig. 5 presents the particle size distribution curves of magnetite ores by different breakage energies.

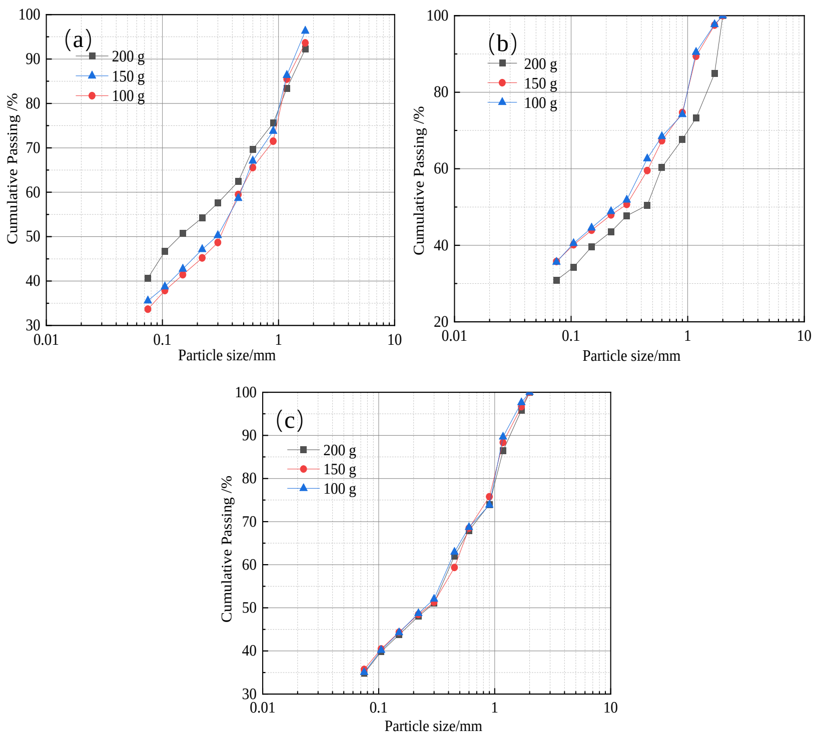

Fig. 5. Effect of breakage energy on particle size distribution of magnetite ore under different mass: (a) 337.49 J; (b) 539.98 J; (c)742.47 J

When the energy is 742.47 J, there is little difference in the broken degree of magnetite particle size distribution, indicating that the further application of energy that exceeds a certain value has little impact on the broken degree of particles (Bonfils et al., 2016). When the energy is 337.49 J and 539.98 J, the particle size distribution differs slightly between comminution products from magnetite ores weighting 100 g and 150 g, but this distribution is obvious in the particle group breakage of those ores weighting 200 g. This is because part of the energy is consumed under the slip action between particles with larger layer thicknesses, and the overlarge thickness of the particle group will affect the crushing effect. Therefore, the particle group with a layer thickness of 1.45 cm was selected for the impact breakage test.

The layer thickness was kept at 1.45 cm to study the effect of particle size on particle group breakage. The magnetite particles are screened according to four sizes (-2.00+1.18 mm, -1.18+0.60 mm, -0.60+0.30 mm, and -0.30 mm) to conduct the impact breakage test by different energies.

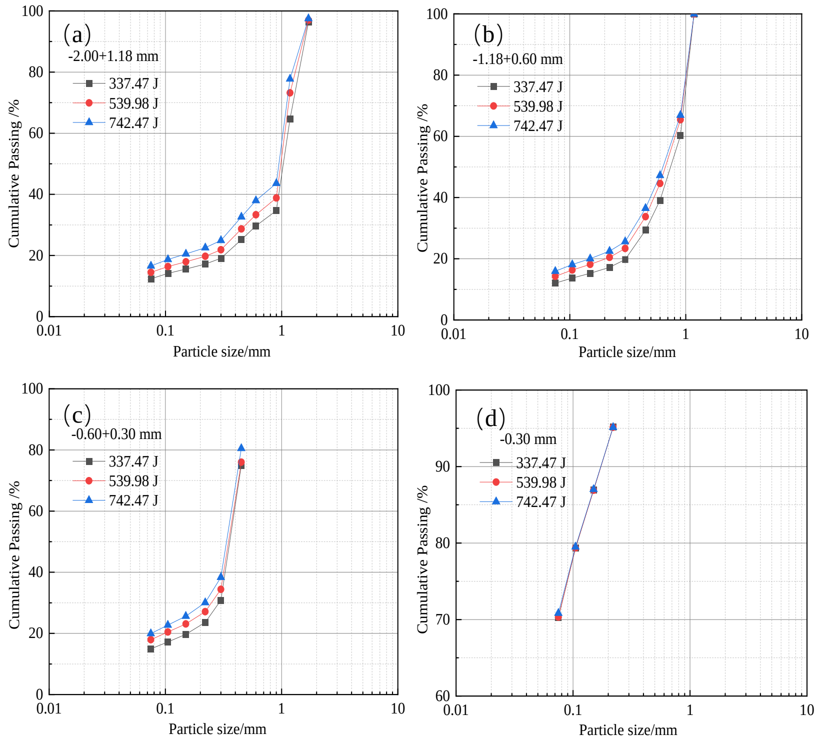

Fig. 6. Effect of particle size on particle size distribution of magnetite ore impact breakage: (a) -2.000+1.180 mm size fraction; (b) -1.180+0.600 mm size fraction; (c) -0.600+0.300 mm size fraction; (d) -0.300 mm size fraction

Fig. 6 presents the particle size distribution curves of magnetite ores in different size fractions by impact breakage. The difference is insignificant in the broken degree of magnetite particles in the size of -0.30 mm, this is because the stress concentration caused by cracks and defects inside magnetite ores in the particle size of +0.30 mm under the action of energy can cause crack propagation and even fracture. In comparison, the crack effect of particles smaller than -0.30 mm is small because they can hardly be broken due to their higher resistance to impact breakage. Therefore, the particle group of -2.00+1.18 mm was selected for the impact breakage test to study ore breakage characteristics.

To sum up, the particle group in the size fraction of -2.00+1.18 mm and layer thickness of 1.45 cm was suitable for the impact breakage test, based on which studied the effect of breakage energies on particle size distribution, particle morphology, and magnetite liberation characterization.

3. Results and discussion

3.1. Fracture morphology analysis

Fracture morphology records the whole course of crack propagation when a material is fractured, based on which we can get information about the fracture cause, mechanism, mode and path, as well as the stress at fracture (Hull, 1999). In this work, the fracture morphology of magnetite ores that were broken into particles in the median size of -10.00+5.00 mm at different energies was observed using SEM to explore fracture morphology law.

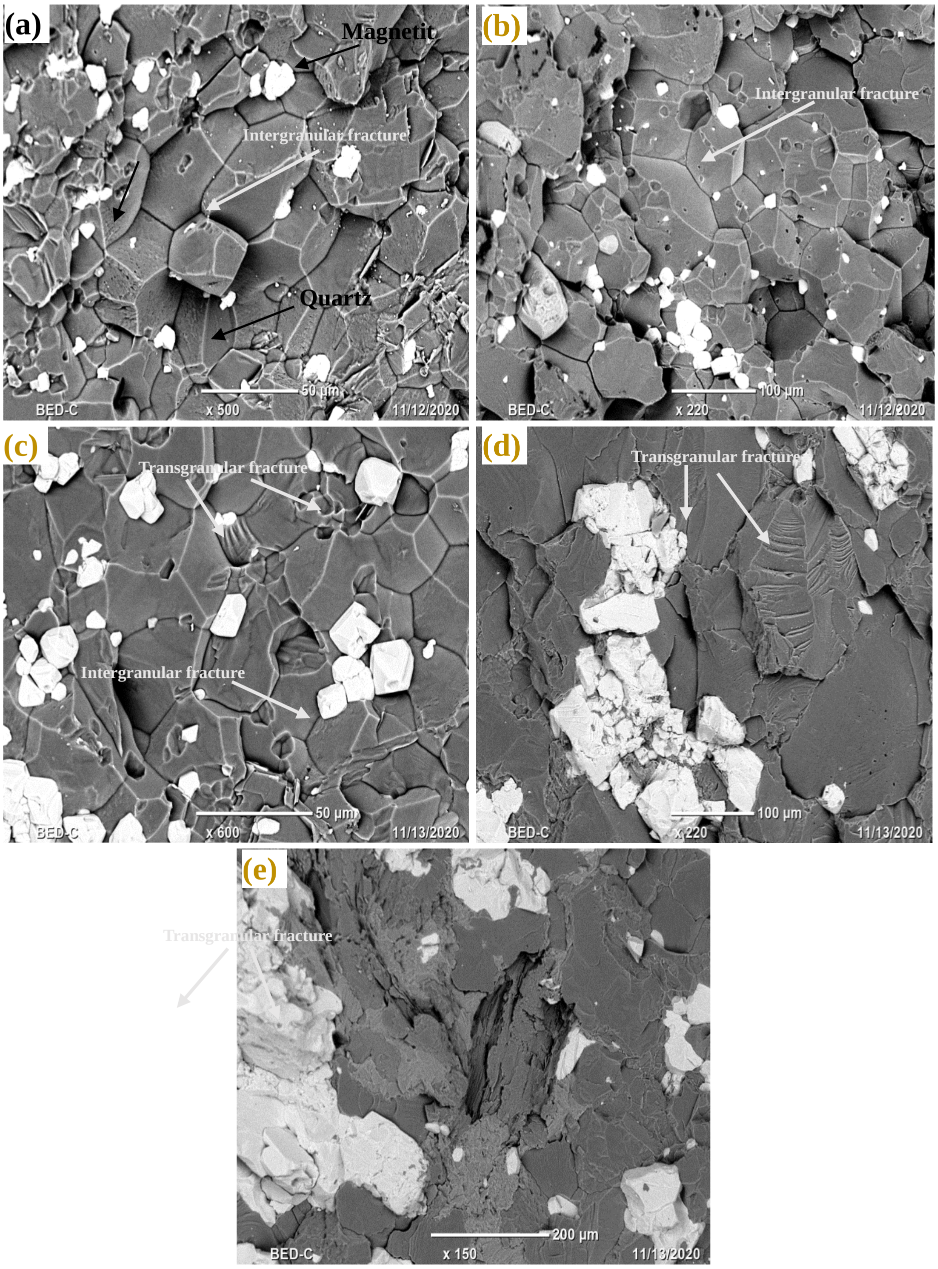

Fig. 7. Fracture morphology characteristics of magnetite ore under different impact energy: (a) 0.62 kwh/t; (b) 0.80 kwh/t; (c) 0.99 kwh/t; (d) 1.17 kwh/t; (e) 1.35 kwh/t

Fig. 7 shows the fracture morphology of magnetite ore by different energies. It can be seen that morphology is significantly affected by energy change. As the energy increases from 0.62 kwh/t to 0.80 kwh/t, magnetite ores present the mode of intergranular fracture. At this time, the fracture morphology shows rock candy patterns with obvious grain shapes (Figs. 7 (a)～(b)). At the energy of 0.99 kwh/t, these ores present intergranular-transgranular coupling fracture, showing obvious lamellar tearing patterns and other transgranular fracture characteristics (Fig. 7 (c)). When the energy ranges between 1.17 kwh/t and 1.35 kwh/t, cracks propagate at higher speeds, causing a tear effect among crystal structures. In this case, the intergranular fracture occurs, which results in a rough fracture surface in these structures. Meanwhile, the fracture morphology shows the characteristics of transgranular fracture, such as step-shaped and lamellar tearing patterns (Figs. 7 (d)~(e)). All in all, the fracture morphology of magnetite ores evolves from intergranular fracture to intergranular-transgranular coupling fracture and finally to transgranular fracture as the energy increases, and the difference in morphology features is caused by different energies.

3.2. Energy and the particle size distribution

3.2.1. Particle size distribution

Different breakage way between particle group and single particle, of which the former's force state depends on particle characteristics and the magnitude of force. In this paper, particle group impact breakage test was carried out at different energies to study the particle size distribution characteristics.

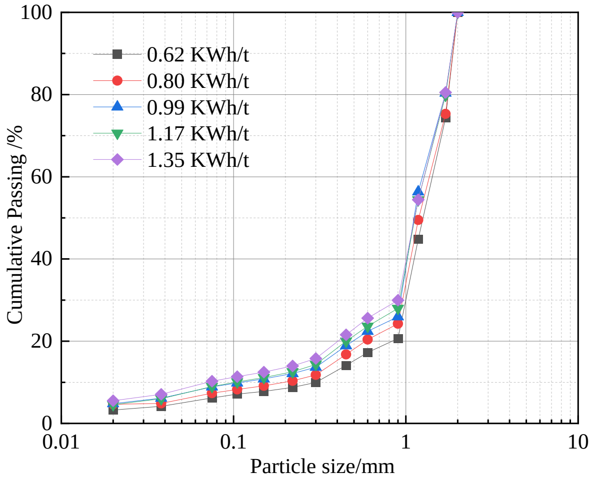

Fig. 8. Particle size distribution curve of magnetite particle bed breakage

As shown in Fig. 8, there is little difference in the size distribution of the magnetite particle group after the impact breakage at different energies. The broken degree is mainly affected by original microcracks and other defects of magnetite ores. According to the theory of particle breakage (Martins et al. 2020), the particle group in the size of -2.00+1.18 mm mainly volume fracture and crack fractures. The smaller the particles, the fewer the original cracks. In this instance, particles are broken in the form of intracrystalline fracture, which consumes a large amount of energy. After the energy reaches a certain level, the continuous application will have little impact on the broken degree of particles. Therefore, the comminution products of magnetite ores show little difference in particle size distribution at different energies. Besides, the particle breakage presents a size effect. That is, the smaller the particles, the stronger the crushing strength, and accordingly the larger the energy needed.

3.2.2. Fractal analysis on particle size distribution

The crack propagation in ores has fractal features at the time of fracture, and the particle breakage is caused by the interpenetration of numerous cracks formed inside these ores under an external force. Results show that the particle size distribution of rocks can be expressed by the fractal dimension, and its distribution equation is written as follows based on mass-particle size relations (Si et al. 2020):

$$\frac{M(r)}{M} = \left(\frac{r}{r_0}\right)^{3\text{-D}} \tag{1}$$

where r refers to the breakage size of rocks; $M(r)$ represents the accumulative mass of particles in the breakage size smaller than r; M is the total mass of breakage size; D is the fractal dimension for particle size distribution.

The fractal dimension for the particle size distribution of the magnetite particle group is calculated based on the fractal theory of particle size to establish a relationship between specific energy and the fractal dimension of particle size.

Fig. 9 presents the relationship between specific energy and the fractal dimension for particle size distribution of the magnetite particle group (D): the value of D increases with specific energy, showing a linear relation between them, and the fitting equation has a coefficient of 0.95. Hence, D is regarded as an indicator representing the particle size distribution of the magnetite particle group by different specific energy.

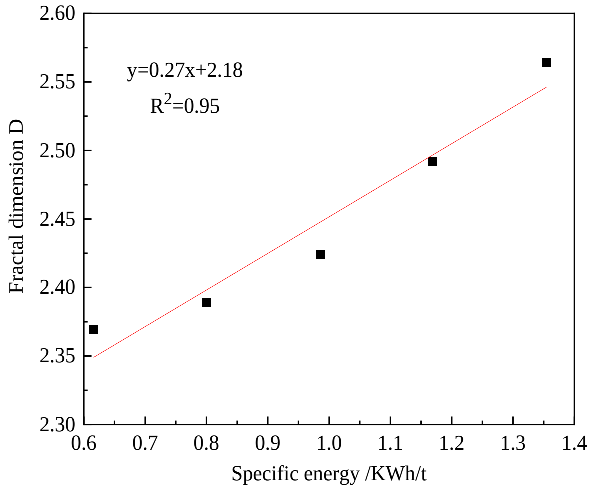

Fig. 9. Relationship between magnetite particle size fractal dimension D and specific energy

3.3. Liberation properties

In the mineral sorting process, ores are breakage and grinding for minerals liberation, and the key of liberation is the amount of energy applied during the impact breakage In this study, therefore, the AMICS-Mining was used to analyze the magnetite liberation degree of the magnetite that was crushed into various sizes at different energies. To ensure the reliability of measured data, more than 20,000 particles were tested in each sample.

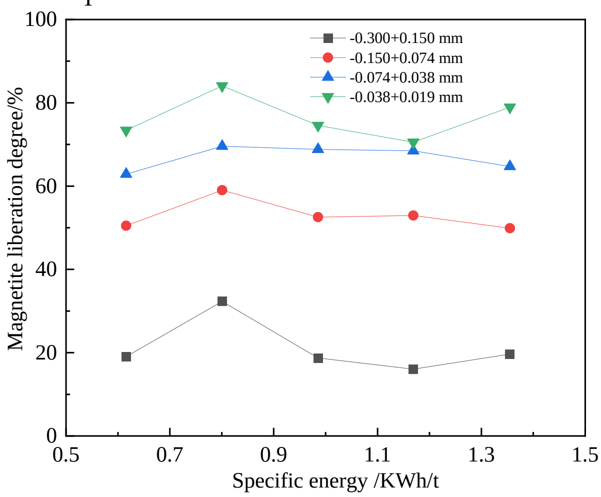

Fig. 10. Liberation degree distribution of magnetite under different specific energy

Fig. 10 exhibit the liberation degree distribution of magnetite under different specific energy. With the rising of specific energy, the magnetite liberation degree of magnetite first increases and then decreases. It is relatively high at the specific energy of 0.80 kwh/t, showing values of 32.31%, 59.04%, 69.57%, and 84.07% in the particle size of -0.30+0.15 mm, -0.15+0.74 mm, -0.074+0.038 mm, and -0.038+0.019 mm, This indicates that magnetite experience the selective breakage at the mineral interface at an appropriate specific energy of 0.80 kwh/t, showing a higher degree of minerals liberation. It can be seen that the particle size of these products and the liberation degree of magnetite are not optimal at the same time. However, since the main purpose of comminution is mineral liberation, followed by appropriate particle size, a proper amount of specific energy is the key to enhancing the liberation degree of comminution products.

4. Conclusions

The paper mainly studies the impact breakage characteristics of magnetite, establishing the relationship between specific energy and the fractal dimension for the particle size distribution of magnetite, analyzing the fracture morphology characteristics of magnetite at different specific energies, and revealing the effect of specific energy on magnetite liberation degree. Finally, this work is concluded as follows:

According to the test on particle group breakage, there is a size effect of particle breakage. That is, the specific energy within a certain range has little impact on the breakage degree of the particle group. The fractal dimension for particle size distribution (D) can be used as an indicator to describe the breakage degree of magnetite quantitatively, and the fractal dimension D of particle size increases with the increase of specific energy, showing a linear mathematical relation.

The fracture morphology of magnetite was analyzed using SEM. Results show that morphology mainly presents intergranular and transgranular fractures. At appropriate specific energy, cracks are fractured along the mineral interface; when the energy is overlarge, cracks are fractured inside crystal structures. With the increase of specific energy, the fracture morphology of magnetite evolves from intergranular to transgranular fracture。

This work reveals the effect of specific energy on mineral liberation behaviors; the magnetite liberation degree first increases and then decreases with the rising of specific energy. The magnetite are fractured at the mineral interface at an appropriate specific energy, which can improves the mineral liberation.

By analyzing the quality of comminution products from magnetite, it is found that particle size and the minerals liberation degree of comminution products are not optimal simultaneously. Suitable specific energy can improve the mineral liberation of comminution products, and avoid over-comminution of products.

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