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Study on the Difference of Microwave Irradiation Effect Caused by the Particle Size Distribution of Rock Minerals

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Abstract: In the process of microwave-assisted rock breaking, there are many factors that affect the rock breaking effect, among which the particle size distribution of minerals has an important influence. In this paper, the samples composed of common minerals calcite and pyrite in rocks were used as the research object, and six kinds of mineral particle size ratio schemes were set up. By using COMSOL multi-physical field coupling analysis platform, a binary medium analysis model was established to study the distribution characteristics and evolution law of electromagnetic field, temperature field, stress field and plastic zone of the model after microwave irradiation. The results showed that the mineral particle size ratio had no significant effect on the size and distribution of electromagnetic field, while the central temperature of the sample increased with the increase of particle size ratio; with the extention of irradiation time, the larger the particle size ratio, the greater the first principal stress of the model, and the tensile zone appeared in pyrite; The larger the particle size ratio, the earlier the initiation time of plastic zone, the larger the area of plastic zone, and the more obvious the difference of morphological characteristics of plastic zone. When the size of minerals in the rock was uniform, the weakening effect of microwave irradiation on the rock was better.

Keywords: Microwave-Assisted, Rock Breaking, The Ratio of Mineral Size, Electromagnetic Field, Plastic Zone

1. Introduction

With the development of microwave heating technology, microwave-assisted mechanical rock breaking [1] has attracted much attention because of its advantages of high efficiency, low noise and energy saving. There are many factors affecting the effect of microwave-assisted mechanical rock breaking, such as the mineral composition of the rock [2], the macro and micro structure [3-6], the microwave irradiation method [7-10], the external conditions [11-12] and so on. As an important embodiment of the macro-micro structure of rock, the particle size distribution of minerals in rock has a significant impact on the effect of microwave-assisted rock breaking. It is urgent to carry out in-depth research to promote the development of microwave-assisted rock breaking theory and technology.

At present, domestic and foreign researchers have conducted a lot of basic research on the effect of mineral particles. Y. Wang et al. [13] studied the thermal stress and crack propagation of rocks under the action of short pulse microwave energy. The results showed that the particle size of minerals would affect the change of thermal properties and the law of crack propagation. Liu Delin [14] found that different mineral content could cause different degrees of damage to the rock models. On this basis, Dai Jun et al. [15] studied the microwave absorption performance of the pyrite combination model by finite difference method, and the results showed that different pyrite particle sizes would lead to different rock yield types. Zou Guanqi [16] established a numerical model and concluded that the size of mineral particles would affect the uniformity of electromagnetic field around minerals under microwave irradiation. The above-mentioned scholars have all studied the influence of the particle size of a single mineral, and some experts have compared the influence of the particle size of the binary medium model. Tang Yang [17] established a rock model composed of quartz and plagioclase by discrete element method using PFC2D numerical software，and it was found that the number of cracks produced by the model would vary with the change of discontinuity scale under microwave irradiation. Abubeker yimam Ali [18] also used PFC2D to irradiate the binary mineral rock on the transparent matrix, and found that the greater the dispersion of minerals, the greater the unlimited compressive capacity of the rock. Although many scholars have done a lot of studies on the effect of mineral particle size, most of them only focused on the size of single mineral particle, and the situation of multi-particle minerals has not been considered, namely, the impact of mineral size distribution on the effect of microwave irradiation.

In this paper, a two-phase rock sample model composed of weak absorbing minerals and strong absorbing minerals was established by using COMSOL multi physical field analysis platform and based on the particle size distribution of real rock meso-structure minerals. The distribution characteristics of electromagnetic field, temperature field, stress field and plastic zone of the model were studied under the condition of different particle size distribution of minerals during microwave irradiation; the influence law and mechanism of mineral particle size distribution on microwave irradiation effect were revealed.

2. Rock Mineral Particle Size Distribution and Analysis Model Abstraction

The particle sizes and shapes of minerals in rocks were different, and the distribution of particle positions was also different. These differences in different degrees would cause changes in the physical and mechanical properties of rocks. In order to study the influence of these differences in particle size distribution on the effect of microwave irradiation on rocks, the distribution position and particle size distribution differences of minerals in real rock samples were extracted and used as the basis for establishing a numerical model. This distribution can not only represent the differences in particle size, but also reflect the differences in position distribution (as shown in Figure 1).

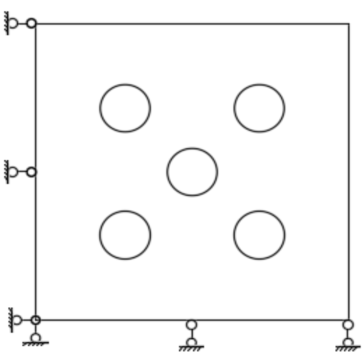


Figure 1. Microscopic photo of alkaline granite thin slices.

In this paper, the influence of particle size distribution difference was studied, so on the premise of maintaining the same particle position in the numerical model, the corresponding numerical analysis model was established by changing the size of the particle size, and the specific establishment process is shown in section 3.

3. Numerical Model

3.1. Establishment of Model

The microwave waveguide used in analysis was WR340, the width of microwave irradiation port was 86.36mm, and the size of microwave heating cavity was 500mm×350mm. In the numerical model, pyrite and calcite were used as strong and weak absorption mineral; the rock was simplified as a binary medium composed of pyrite and calcite. Since the size of the mineral could affect the distribution of the electromagnetic field, in order to eliminate the heating deviation caused by this influence in minerals, the mineral size of 14mm was selected in the test. The size and position of the whole model were shown in Figure 2. As the irradiation sample model was shown in Figure 1(b), the shape of pyrite was set as a near circle which was common in nature and was distributed in calcite, R_{max} (maximum particle size mineral) pyrite particles were located in the center of the sample, R_{min} (minimum particle size mineral) was located in the same centroid around the center. This position distribution eliminated the influence of the dispersion degree between the mineral particles on the test. Its movement was constrained by a fixed support at the model boundary with an initial temperature of 20°C, microwave irradiation frequency of 2.45GHz and microwave irradiation power of 1kW.

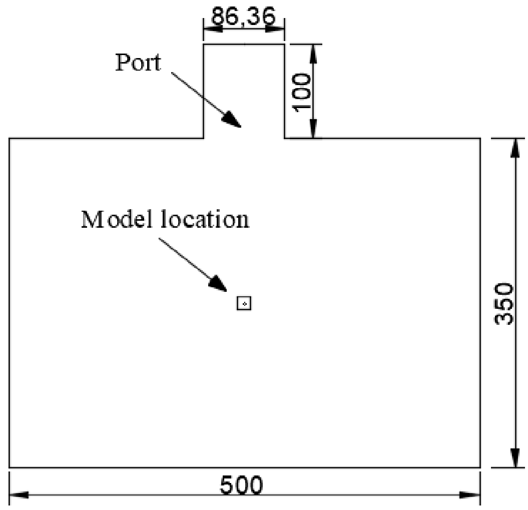


Figure 2. Microwave heating mineral model (mm).

3.2. Research Plan

The research of particle size was usually realized by changing the average particle size R or the particle size ratio $Rc=R_{max}/R_{min}$, As the main rock-forming mineral, pyrite was divided into giant, coarse, medium, fine, and micro. This study maintained the same mineral content by changing the maximum and minimum size of mineral particles, designing 1.0, 1.2, 1.4, 1.6, 1.8, 2.0. The numerical model was shown in Figure 3. The value of particle size ratio Rc was used as the quantitative index of particle size distribution, aiming to study the effect of particle size distribution on the effect of rock destruction.

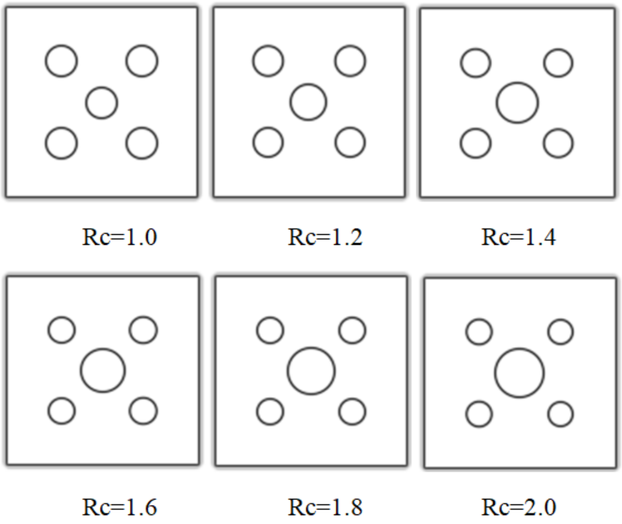


Figure 3. *Schematic diagram of mineral model with different particle size ratio (circular minerals are strongly absorbing minerals).*

The mineral electromagnetic, mechanical and thermodynamic parameters of minerals were shown in Table 1.

Table 1. *Mineral parameters [9, 13, 14].*

Parameter name	Pyrite	Calcite
Relative permeability	1	1
Relative permittivity	-17j	-0.00004j
Cohesion/MPa	25	25
Internal friction angle/°	54	34
Poisson's ratio	0.16	0.32
Young's modulus/GPa	292	72.9
Coefficient of thermal expansion/$\times 10^{-6}$	27.3	13.1
Thermal conductivity/W/m·k	37.9	4.02
Specific heat capacity/J/Kg·k	517	817
Density/kg/m^3	5018	2608

4. Results and Discussion

The changes of the rock internal electromagnetic field, temperature field, stress field and plastic zone in the six groups of samples were analyzed under the same microwave irradiation power.

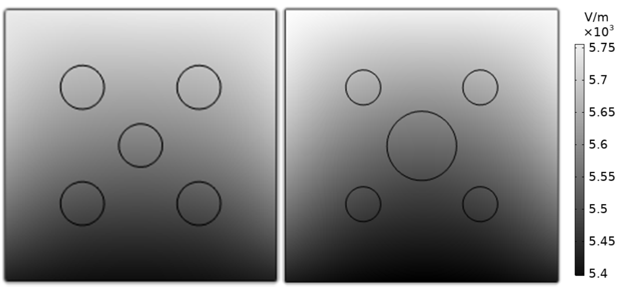


Figure 4. *Electric field intensity diagram with particle size ratio of 1.0 (left) and 2.0 (right).*

4.1. Electromagnetic Field Analysis

In order to eliminate the influence of uneven electromagnetic field, it was necessary to ensure that the electromagnetic field in each sample was relatively uniform. Figure 4 showed the electric field distribution diagram of samples particle size ratios of 1.0 and 2.0. Under the two schemes, the standing wave ratio was 1.06653 and 1.06624 respectively, and the electromagnetic field was uniform. Other schemes were 1.06657, 1.06682, 1.06736 and 1.06719 respectively.

4.2. Temperature Field Analysis

The most obvious characteristic of microwave irradiation was the rise of rock mineral temperature. Due to the different dielectric constant of each mineral, the absorption of electromagnetic waves varied and the heating effect varied significantly. Figure 5 was the temperature distribution diagram of samples with different particle size ratios when the irradiation power was 1kW and the irradiation time was 14 s.

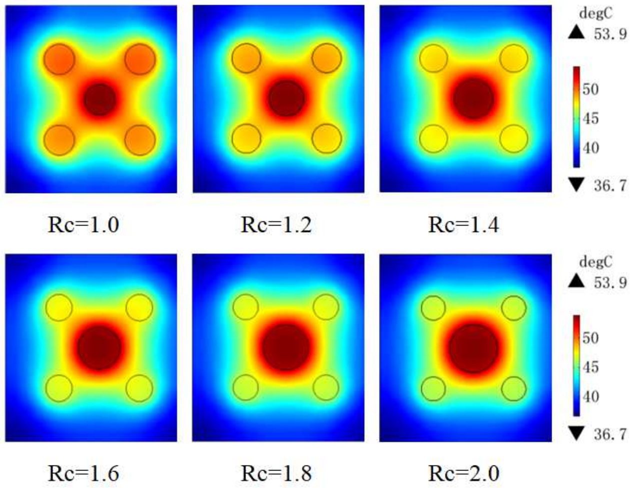


Figure 5. *Temperature distribution of mineral model.*

It can be seen from figure 5 that the temperature of pyrite, as a strong microwave absorbing mineral, was significantly higher than that of calcite after microwave irradiation. The maximum value of the sample temperature appeared at the center of the largest pyrite particle size. Under the same irradiation conditions, the high temperature area gradually increased with the increase of the maximum particle size in the center, while the temperature of the surrounding particles with the minimum particle size would become lower and lower. Take the model with a particle size ratio of 1.0 and 2.0 for example, the high temperature region range and the highest temperature at Rc=2.0 were higher than that at Rc=1.0 model.

It was found that the highest temperature of models with six particle size ratio was generated at the center of pyrite with the largest particle size R_{max}, and the lowest temperature was at the edge of the model. In order to further study the temperature distribution and change trend of samples with different particle size ratios irradiated by microwave, the curves of the maximum temperature change of pyrite the model at five times of 2s, 4s, 6s, 8s, and 10s were given in figure 6.

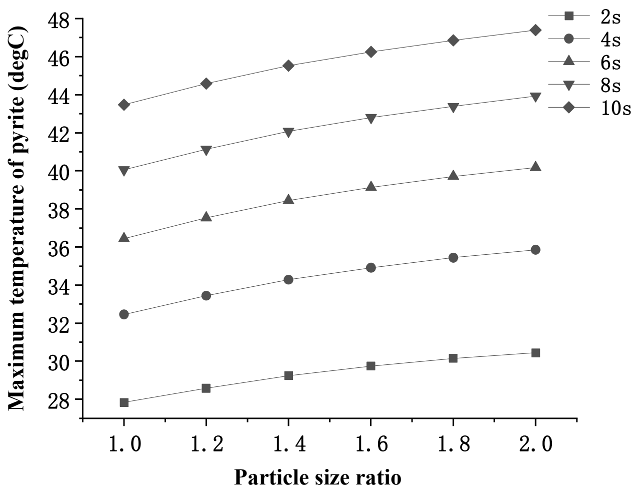


Figure 6. *Maximum temperature variation curve of mineral model.*

As shown in Figure 6, the highest temperature of the model increased with the increase of irradiation time at the same particle size ratio, especially from the 2s to 6s at the initial onset of irradiation. Taking Rc=2.0 as an example, the highest temperature of the initial irradiation model increased by 10.1°C, while the highest temperature increased by 7.2°C between 6s and 10s. It was because pyrite itself quickly absorbed energy to increase its temperature, and then transferred heat to calcite matrix with the increase of irradiation time, so the central temperature rate decreased.

With the increased of particle size ratio, the maximum temperature of pyrite with large particle size in the center would also increase by about 5°C. In contrast, the lowest temperature of the model was associated negatively with the particle size ratio. This phenomenon occurred because the pyrite in the center of the model increased with the increase of particle size ratio, the larger the content of pyrite in the center, the higher the temperature of the R_{min} pyrite particles in the surrounding area, the R_{min} pyrite and the lowest temperature at the sample boundary.

4.3. Stress Field

When the thermal stress of rock irradiated by microwave exceeded the ultimate stress of rock, damage and failure would occur. Therefore it was very necessary to analyze the stress of samples of mineral models with different particle sizes after microwave irradiation.

When the irradiation power was 1kW and the irradiation time was 14s, the first principal stress distribution of the sample was shown in Figure 7 (tension was positive, pressure was negative), the first principal stress inside the calcite matrix was positive, which was in tension, The first principal stress of the R_{max} particles at the center of the pyrite was negative, which was the compressive stress. This was because pyrite was a wave-absorbing mineral with a large coefficient of thermal expansion, which absorbed heat and expands after microwave irradiation, but it was constrained by calcite, a weak microwave sensitive mineral, so the interior of pyrite was subjected to compressive stress, while the calcite matrix was pulled by the expansion of pyrite. During the process of particle size ratio varied from 1.0 to 2.0, the maximum compressive stress of the model was always in the center of R_{max} pyrite particles.

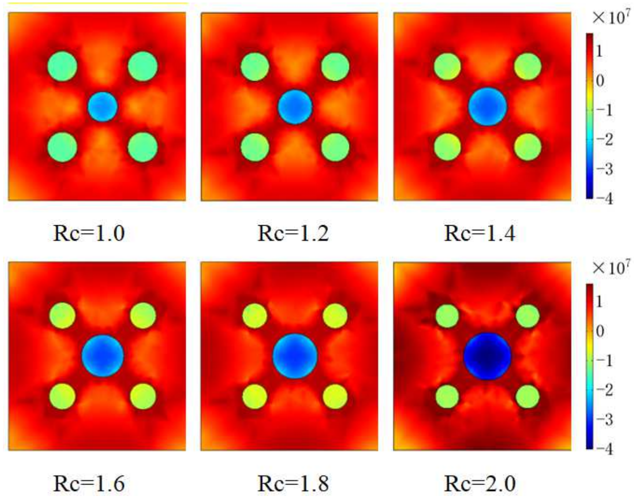


Figure 7. *Distribution cloud diagram of the first principal stress of minerals.*

Figure 8 was a graph of the maximum tensile stress of samples with different particle size ratio at 2s, 4s, 6s and 8s under microwave irradiation. It could be seen that with the increase of particle size ratio, the content of pyrite with large particle size in the center increased, the more microwave energy was absorbed, and the higher the temperature rose, the greater the expansion effect on calcite, so the maximum tensile stress of calcite matrix showed an upward trend, and the maximum tensile stress of minerals increased significantly with the increase of irradiation time, which showed that the particle size ratio had a significant effect on the first and second tensile stress of calcite matrix during irradiation.

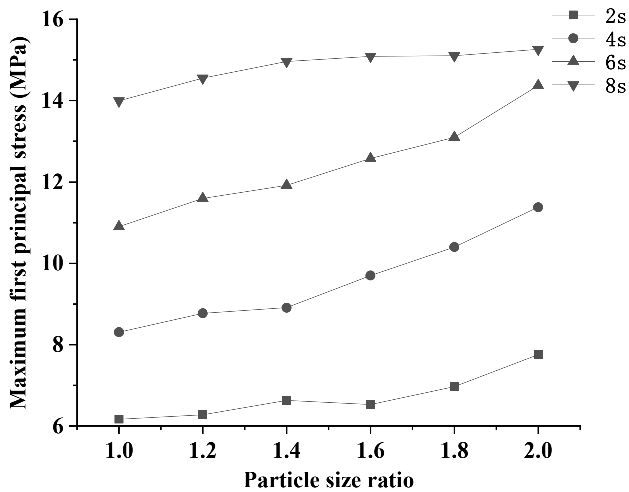


Figure 8. *Maximum tensile stress curve of the model.*

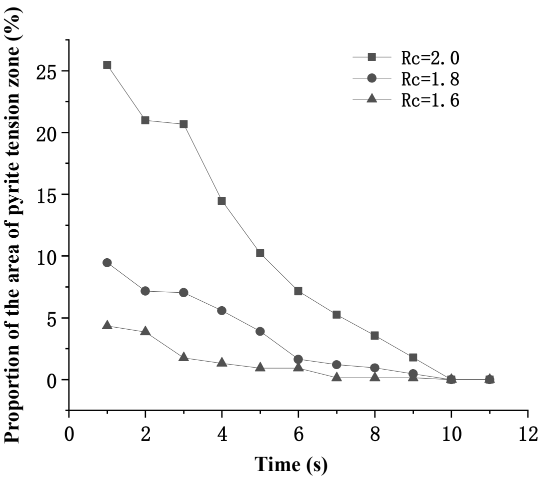


Figure 9. *Curve of the area percentage of the tension zone of pyrite.*

In order to further analyze the influence of particle size ratio on the first principal stress, the proportion of tensile area of pyrite particles (the ratio of tensile area of pyrite to total area of pyrite) with the increase of irradiation time was calculated. As shown in Figure 9, at the initial stage of irradiation, the area of the pyrite tension zone was larger, and the larger the particle size ratio, the larger the area of the tension zone, but it gradually decreased with time, and finally the tensile area becomes 0. At this time, pyrite was all under pressure. This was because in the initial stage of irradiation, the strong wave-absorbing mineral absorbed energy, and the temperature rose rapidly, resulting in a higher temperature gradient at the critical point between pyrite and calcite, which produced greater thermal stress, and the formation of thermal stress at the boundary of pyrite. With the increase of the irradiation time, the plastic zone within the model with different particle size ratios appeared and developed, the stress and strain were released, which reduced the area of pyrite tension zone.,

It was found that the tensile area of pyrite only appears at R_{min} particle position of the model with particle size ratio of 1.6, 1.8 and 2.0. In order to analyze this reason, all the first principal stresses on a transversal line of the model were calculated in the test. As shown in Figure 10, the most central position of the sample was (0, 0), the starting point of the section was (7, 7), and the end point was (-7, -7). Since the model size was 14mm × 14mm, so it was an axisymmetric line of 45° of the model. The transversal line penetrates the calcite matrix, R_{max} pyrite particles, and R_{min} pyrite particles, and the first principal stress of the minerals at different positions on the section line was analyzed.

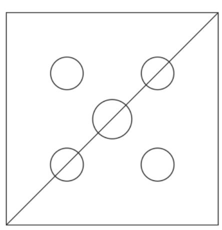


Figure 10. *Two-dimensional transversal line diagram of rock model.*

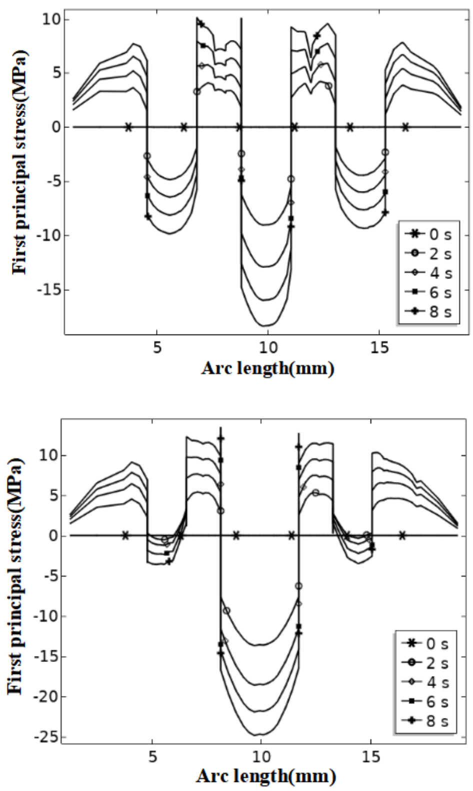


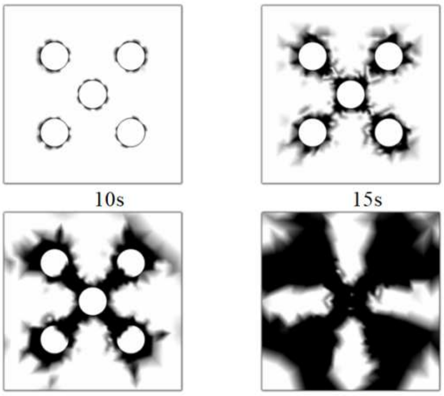
Figure 11. *First principal stress curve of rock model along two-dimensional transversal.*

Figure 11 showed the curve of the first principal stress along the two-dimensional transversal at 0s, 2s, 4s, 6s and 8s when the particle size ratio was 1.0 and 2.0. It could be seen that the first principal stress suddenly changed at the junction of pyrite and calcite. When the particle size ratio was 1.0, the first principal stress changed from the tensile stress in calcite to the compressive stress in pyrite, and the maximum tensile stress occurred at the junction of calcite and pyrite. When the particle size ratio gradually increased to 2.0, a tensile area would also appear in a small part of pyrite near the junction of pyrite and calcite. With the increase of time, the tensile area would gradually decrease to 0.

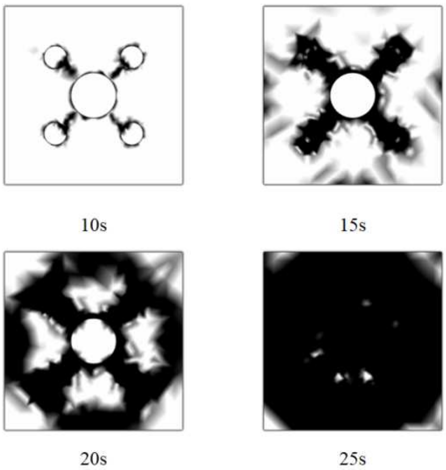
By comparing the first principal stress curve of two-dimensional transversal of six groups of particle size ratio models, it was found that R_{min} pyrite particles had tensile zone only when the particle size ratio was 1.6, 1.8 and 2.0. This was because when the particle size ratio was small, the particle size distribution was uniform, the mineral temperature gradient was small, and the thermal stress was relatively small. With the increase of particle size ratio, the temperature distribution of R_{min} and R_{max} pyrite particles was extremely uneven, and the thermal stress was large. Therefore, the thermal stress at its boundary would first exceed its own strength limit and destroyed. This was also the reason for the preferential initiation of plastic zone at R_{min} boundary. From the above analysis, it could be seen that the mineral particle size ratio had a significant impact on the first principal stress distribution in the specimen. The larger the particle size ratio, the greater the tensile stress at the pyrite particle boundary and the smaller the compressive stress inside pyrite.

4.4. Plastic Zone

Due to the different particle morphological characteristics of minerals in rock samples, the development law of plastic zone was different in the process of microwave irradiation. In this paper, the development law and mechanism of the plastic zone with different particle size ratio models were analyzed when microwave power was 1kW and irradiation time was 10s, 15s, 20s, and 25s.



(a) Particle size ratio Rc=1.0



(b) Particle size ratio Rc=2.0

Figure 12. *Schematic diagram of plastic zone development in different particle size ratio models.*

Figure 12 showed the development shape of the plastic zone of the model at four moments when the particle size ratio was 1.0 and 2.0. The plastic zone first sprouted at the pyrite boundary and slowly expanded to the surrounding calcite matrix as the irradiation time increases. The plastic zone between the R_{max} and R_{min} mineral particles formed a connection and gradually developed inside the pyrite, and finally the plastic zone developed radially from pyrite to the edge of the matrix. By comparing the models with the particle size radio Rc = 1.0 and Rc = 2.0, it was found that there were significant differences in the development of plastic zone in different particle size ratio models at the same time, and the difference in the development of plastic zone became more and more obvious with the extension of irradiation time. The results showed that the larger the particle size ratio, the more obvious the weakening effect on the rock after microwave irradiation.

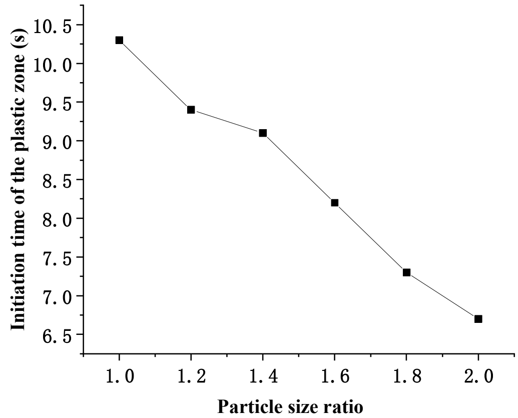
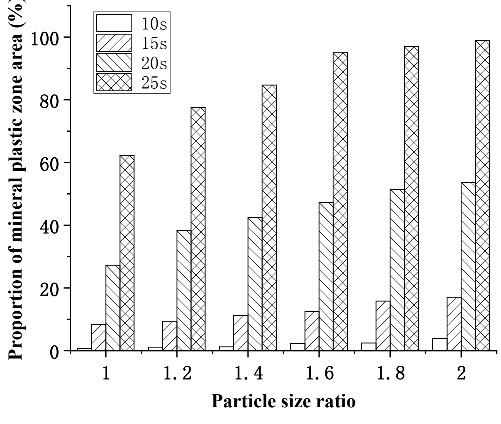
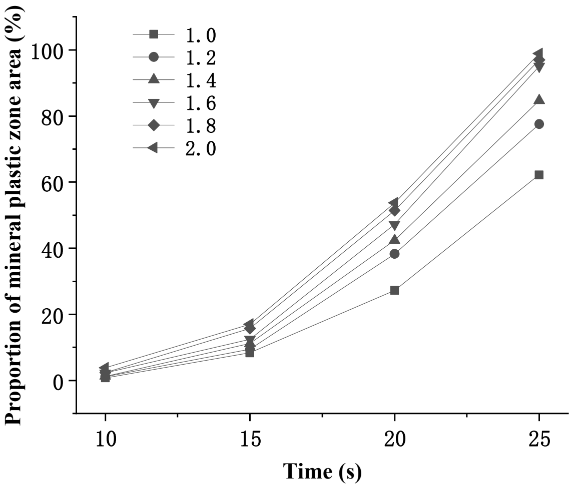


Figure 13. *The initiation time curve of the plastic zone with different particle size ratios.*

The initiation time of plastic zone was also an important index to describe the development form of plastic zone. The earlier the plastic zone appeared, the better the weaking effect of model rock. Figure 13 showed the initiation time of pyrite plastic zone in models with different particle size ratios. It could be clearly seen from the graph that when Rc = 2.0, pyrite samples first initiated plastic zone in 6.5s, followed by models with particle size ratios of 1.8, 1.6, 1.4 and 1.2, while Rc = 1.0 produced plastic zone at the latest in 10.3s. This was because in the damage initiation stage, the model with large particle size ratio would produce large thermal stress, and a tensile zone would be formed at the pyrite boundary, resulting in the failure at the boundary. Therefore, the model with larger particle size ratio would produce a plastic zone first. This indicated that under the same irradiation conditions, the earliest time of plastic zone in different particle size ratio models was different, and the time of plastic zone would be earlier and earlier with the increase of particle size ratio.



(a) Histogram of the change of the plastic zone with the particle size ratio under the same irradiation time



(b) Variation curve of plastic zone with microwave irradiation time

Figure 14. *Proportion of plastic area of model with different particle size ratio.*

The area ratio of plastic zone is defined as the ratio of the area of plastic zone to the total area of minerals. In this paper, the change of the area ratio of mineral plastic zone in different particle size ratio models after 10 s, 15 s, 20 s and 25 s microwave irradiation under 1 kW microwave irradiation power was analyzed. Figure 14(a) was a histogram showing the change of plastic zone with particle size ratio, and Figure. 14(b) was a curve showing the change of plastic zone with microwave irradiation time.

It could be observed from Figure 14(a) that, the area proportion of the mineral plastic zone showed an upward trend with the increase of the particle size ratio at four times of 10s, 15s, 20s, and 25s, and the difference of plastic zone development was obvious at different times. As could be seen from Figure 14(b), taking the particle size ratio Rc = 1.0 and Rc = 2.0 as examples, when the particle size ratio was 1.0, the area proportion of plastic zone at four times is 0.7%, 8.3%, 27.2% and 62.2% respectively, and the area proportion of plastic zone only increased by 7.6% in 10s ~ 15s, while it increased by 18.9% and 34.9% in 15s ~ 20s and 20s ~ 25s, and the latter was 2.5 ~ 4.8 times that of the former. When the particle size ratio was 2.0, the plastic area accounted for 3.8%, 17.0%, 53.7% and 98.9% at the four moments. During this period, the area proportion increased by 13.1%, 36.4% and 45.2%. The plastic area proportions of the model with particle size ratio of 2.0 were higher than those of other models in the whole process of microwave irradiation. When the particle size ratio was the same, the proportion of plastic zone area increased slowly in the initial 10s ~ 15s of irradiation. With the increase of irradiation time, the plastic zone area expanded rapidly in 15s ~ 25s, and the larger the particle size ratio, the more significant the plastic zone area of the model developed in the last 10s. This showed that the larger the particle size ratio, the better the damage effect of microwave irradiation on rock.

The main reason for the plastic zone of minerals was that the first principal stress of mineral particles exceeded the strength limit of lock. Under the same microwave irradiation environment, the different temperature and particle size ratio of minerals would affect the first principal stress of mineral particles. The model with large particle size ratio would produce plastic zone first because a small part of R_{min} pyrite would produce tensile zone at the boundary and inside under short-time microwave irradiation, which would lead to tensile failure. With the increase of irradiation time, the tensile stress and compressive stress caused the tensile and compressive failure of the whole R_{min} pyrite particles at the same time, and the area of the plastic zone quickly penetrated between R_{max} and R_{min}. For the model with a relatively small particle size ratio only had a tension zone at its boundary, and there was no tension zone inside the pyrite, which caused the plastic zone to develop slowly. Therefore, when the content of strong absorbing minerals in rock was the same and the microwave irradiation environment was the same, the mineral sample with a larger particle size ratio would have a better degradation effect on the rock by microwave irradiation.

5. Conclusions

In this paper, the binary medium model of pyrite and calcite with the same content and different particle size ratio was established by COMSOL simulation software. The microwave irradiation results of numerical simulation test were analyzed, including the overall and local electromagnetic field strength, the overall temperature characteristics of the sample, the stress strength distribution and the evolution of plastic zone. The conclusions were as follows:

The mineral particle size ratio had little effect on the electric field strength. When the mineral content was the same and the area of microwave cavity was small, the change of mineral particle size ratio in the sample had no significant effect on the overall electromagnetic field.

Due to the increase of pyrite particle content in the center, the maximum temperature in the center of the sample would gradually increase with the increase of particle size ratio. On the contrary, the minimum temperature would decrease with the increase of particle size ratio.

With the increase of particle size ratio, the maximum tensile stress of the sample showed an upward trend and appeared a tensile zone inside the pyrite at the initial stage of irradiation, and the specimen with a larger particle size ratio had a larger area of the pyrite tensile zone.

After microwave irradiation, the plastic zone first appeared in the boundary between pyrite and calcite, and the plastic zone expanded continuously to form a transmissive zone between pyrite R_{min} and R_{max} particles, and finally radially extended to calcite matrix. Under the same irradiation conditions, the specimen with larger particle size ratio would not only sprout the plastic zone first, but also accelerate with the extension of time. The results showed that the larger the particle size ratio, the better the weakening effect of microwave irradiation on rock.

This paper mainly studies the influence of the size difference of minerals on the weakening effect of rock irradiated by microwave under the same microwave irradiation conditions. The research factors are relatively single. This study should deeply study the influence of mineral distribution location, and the influence effect of the comprehensive factors of mineral size and location can be considered at the same time.

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