STUDY ON HEATING CHARACTERISTICS OF GRANITES WITH DIFFERENT SIZES IN MICROWAVE FIELD

by

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Studying the heating characteristics of rocks in a microwave field is fundamental to exploring the mechanism of microwave rock breaking. Therefore, a heterogeneous granite model was established using COMSOL Multiphysics to deeply analyze the specific influence of rock size on rock heating characteristics in a microwave field. The results show that with the increase of rock size, the heating rate of rock exhibits a fluctuation characteristic. This phenomenon occurs because changes in rock size leads to variations in both the magnitude and spatial arrangement of electric field intensity. Further analysis of the electromagnetic loss of granite reveals that increasing rock volume can significantly enhance microwave energy utilization efficiency. Additionally, biotite occupying only 8% of the rock volume, absorbs over 55% of the microwave energy, highlighting the significant impact of biotite content on the heating characteristics of granite.

Key words: *microwave heating, sizes effect, numerical model, granite*

Introduction

During the excavation of deep extremely hard rock layers, mechanical rock-breaking methods such as TBM may encounter serious cutter wear issues, while traditional blasting methods have low efficiency and significant disturbance [1-3]. Consequently, novel assisted rock breaking approaches such as high pressure water jet, laser [4, 5], and microwave have emerged in recent years. Among these, microwave-assisted rock breaking technology is recognized as a promising method with practical applications and has garnered considerable attention [6-9]. The primary cause of rock damage in microwave field is attributed to thermal stress resulting from the rapid heating of rock within the microwave field. Therefore, investigating the heating characteristics of rock under microwave irradiation is essential for understanding the mechanism of microwave rock breaking [10]. In addition, some scholars noticed the effect of size on the efficiency of microwave rock breaking [11]. The Gao *et al.* [12] explored the heating and fracture properties of sandstone of varying sizes under microwave treatment, demonstrating that the size of the rock has a notable impact on the heating rate and fracture characteristics.

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Ma *et al.* [13] indicated that larger rock surface sizes led to reduced length and width of fractures in basalt subjected to microwave irradiation. These findings underscore the significance of the rock size effect on the efficacy of microwave-induced rock fracturing.

To investigate this further, the COMSOL Multiphysics was used to analyze the temperature rise differences in granite of various sizes in microwave field. A heterogeneous model considering the mineral composition of granite was established，and from the perspective of electromagnetic energy loss, the impact of mineral distribution and composition on the heating characteristics of granite and the efficiency of microwave energy utilization was further analyzed.

Model construction

Geometry model and parameter settings

The multimode microwave cavity established in this article is designed in a cubic shape, with a side length of precisely 400 mm. At the center of two opposing sides of the cavity, two BJ26 rectangular waveguides operating at 2.45 GHz in TE10 mode are positioned, and these waveguides are positioned perpendicularly to each other.

The granite sample models are five cylinders with different diameters and the same height-diameter ratio (2:1), which were numbered D30, D40, D50, D60, and D70 (according to the diameter). A discretized granite model constructed by using the software package for Polycrystalline generation Quei *et al.* [14]. In this model, the heterogeneity of rock materials is represented by 3-D Voronoi tessellations of polyhedral cells. Based on the composition of different diagenetic minerals, the polyhedral cells within each granite model are categorized into four groups – plagioclase, quartz, feldspar, and biotite. Each group is assigned specific material properties, with proportions of 45%, 27.5%, 19.5%, and 8%, respectively.

Analysis of the heating characteristics of granite with different sizes

Figure 1(a) shows the temperature distribution of granite samples of different sizes after 300 seconds of microwave irradiation at 3 kW. The results indicate notable disparities in the temperature field distribution characteristics among granite samples of different sizes. Typically, smaller samples exhibit high temperature regions at the sample edges, whereas larger samples show these regions more centrally. Although there is no consistent pattern in the temperature distribution across different granite sizes, there are noticeable fluctuations in average temperature, maximum temperature, and temperature gradient with increasing sample diameter. Additionally, it is important to note that while the average temperatures of samples D30, D50, and D70 are similar, there are substantial differences in their maximum temperature and temperature gradient, as shown in fig. 3.

Analysis of the electric field distribution illustration, fig. 2, reveals a clear correlation between the high temperature zone and the area of high electric field intensity, indicating that the temperature distribution within rock in microwave fields is mainly influenced by the electric field. Of particular note is that the D30 sample exhibits a higher peak electric field value compared to the D50 sample, yet the maximum temperature attained by the former remains lower than that of the latter consistently. This observation indicates that the heating behavior of granite is governed by both the electric field distribution and the mineral composition. Furthermore, analysis of fig. 1(b) shows that during microwave irradiation, the maximum temperature initially increases rapidly, followed by a gradual decline in growth rate. A clear inflection point can be discerned in the heating curve, with a delayed turning point associated with higher initial heating rates. The relationship between temperature gradient and irradiation time shows similarities to that of maximum temperature, with the difference being that the temperature

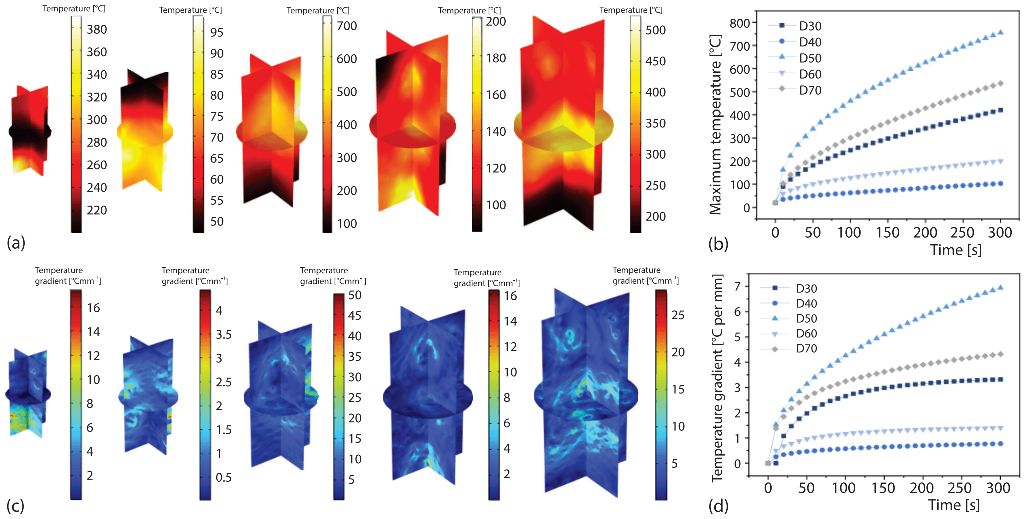

Figure 1. Thermal behavior of granite sample; (a) diagram of temperature distribution, (b) evolution of max temperature with time, (c) diagram of temperature gradient distribution, and (d) evolution of temperature gradient with time

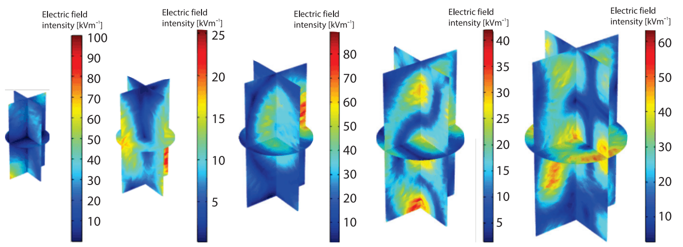

Figure 2. Electric field intensity distribution

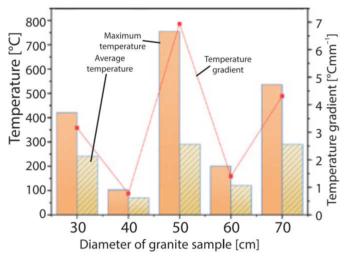

Figure 3. Temperature of granite with different sizes

gradient tends to stabilize more significantly after the inflection point. This phenomenon is attributed to the rapid heating of granite within high field strength regions under microwave influence, which increases temperature differentials between various rock zones and enhances heat transfer rates. With the increase of microwave action time, the heat exchange between different regions gradually balanced. Consequently, the growth rates of maximum temperature and temperature gradient gradually decrease.

The uneven expansion of rock due to different heating rates is a key factor influencing rock damage [15]. Therefore, areas with high temperature gradients at the interface between high and low temperature regions are usually more prone to visible fractures. Figure 1(c) presents an illustration depicting temperature gradients, showing that regions with high temperature gradients are mainly located at the edges of high temperature zones, and the distribution of temperature gradients shows significant discreteness. This phenomenon indicates that the arrangement of granite minerals has a significant influence on temperature.

Analysis of the electromagnetic power loss of granite with different sizes

The energy efficiency of microwave treatment is influenced by both dielectric loss and electric field intensity [16], while the microwave frequency and vacuum permittivity remain constant. Figure 4 illustrates the average electric field intensity and average electromagnetic power loss density of various sizes of granite. The fluctuation patterns of the average electric field intensity within different granite sizes resemble those of average temperature, with the D30, D50, and D70 samples showing a consistent increasing trend in electric field intensity. Although the D70 sample has a higher average electric field intensity than the D50 sample, this leads to differences in the rules of variation in electric fields and temperature. This underscores the combined impact of electric field distribution and mineral distribution on the heating characteristics and temperature distribution features of granite.

Figure 5 depicts the distribution of power loss density within granite, revealing differing abilities of various minerals to absorb energy in a microwave field. The dielectric properties of minerals play a significant role in the efficiency of rock microwave energy utilization. To further quantitatively assess the microwave absorption capabilities of various minerals present in granite, fig. 6(a) depicts the associated power loss density of each mineral. The analysis shows that biotite exhibits significantly higher microwave energy absorption capabilities compared to the other three minerals. For instance, in the D50 sample, electromagnetic power losses for biotite, plagioclase, potassium feldspar, and quartz are measured at 14.91 MW/m^3, 1.54 MW/m^3, 0.65 MW/m^3, and 0.50 MW/m^3, respectively. Despite biotite comprising only 8% of the rock's volume, it absorbs 55% of the total microwave energy absorbed by granite. Consequently, the presence of biotite has a substantial impact on the heating properties of granite when exposed to microwave radiation. Furthermore, considering that the predominant diagenetic minerals in granite are low dielectric loss materials such as feldspar and quartz, its efficiency in utilizing microwave energy is very limited [17].

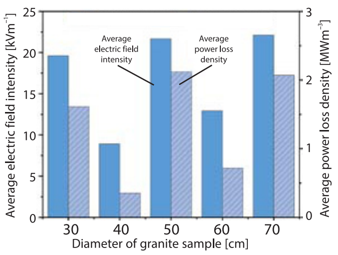

Figure 4. Power loss density of granite with different sizes

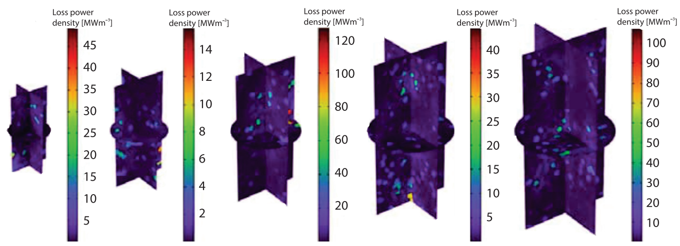

Figure 5. Power loss density distribution

The focus of this study is solely on heat transfer within rock samples, disregarding additional physical effects, with all electromagnetic loss power converted into heat energy. Based on the data in fig. 6(c), it is clear that the microwave absorption capacity of granite samples D50, D60, and D70 significantly exceeds that of D30 and D40 specimens. This observation suggests a strong correlation between power absorption levels and the volume of rocks within the microwave field. In order to quantitatively characterize the microwave energy utilization efficiency of granite, the heat over microwave efficiency (HOME) [18] of each size sample was calculated, which represents the ratio of heat energy to total microwave energy. The HOME values for granite samples of varying sizes are 2.3%, 1.2%, 14.1%, 8.1%, and 37.2%, respectively. The data indicates that microwave energy utilization efficiency is notably low when the rock size is small. Despite minimal differences in average temperature among D30, D50, and D70 samples, the energy utilization rate of the D70 sample surpasses that of the D30 sample by a factor of 17. This observation highlights the substantial improvement in microwave energy absorption efficiency with increasing rock volume.

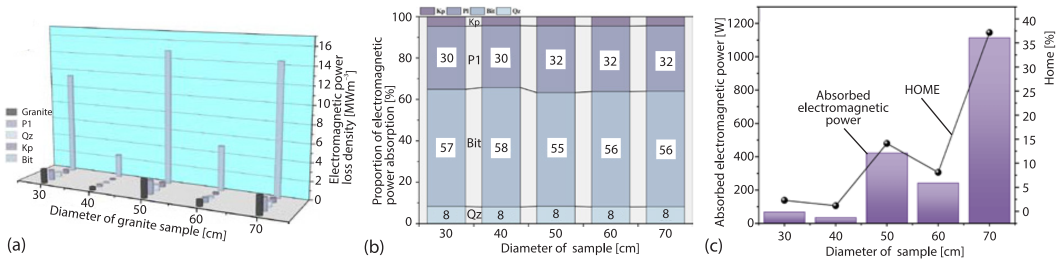

Figure 6. The utilization of microwave energy in granite and diagenetic minerals; (a) power loss density of various diagenetic minerals, (b) proportion of absorbed electromagnetic power of various diagenetic minerals, and (c) absorbed power and heat over microwave efficiency of granite with different sizes

Conclusion

In the microwave field, the temperature, temperature gradient, and electric field strength of granite exhibit periodic variations with increasing sample size. The electric field intensity directly affects the temperature distribution within the rock, while mineral distribution plays a critical role in determining the temperature gradient. Although constituting only 8% of the total composition, biotite in granite absorbs over 55% of the microwave energy, highlighting the significant influence of biotite content on the rock's heating properties. As the volume of the rock increases, microwave energy utilization efficiency also increases. However, achieving high efficiency in microwave rock breaking requires maintaining a high heating rate while optimizing energy utilization.

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