EFFECT OF MICROWAVE IRRADIATION DIRECTION ON TENSILE PROPERTIES OF GRANITE BRAZILIAN DISC TEST

by

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Investigating the tensile properties of rock under varying microwave irradiation directions is essential for understanding the mechanical behavior of microwave-induced rock breaking. A continuous-discrete method is employed to analyze the tensile properties of granite disc samples under three different microwave irradiation directions. The results indicate the variable tensile properties of granite Brazilian disc under different microwave irradiation directions.

Key words: *microwave, Brazilian test, numerical model, granite*

Introduction

Recently, the microwave assistance rock breaking has emerged as a promising innovative method, particularly in the excavation of deep hard rock [1]. The mechanical properties of rock after microwave irradiation are a prerequisite for the application of microwave-assisted rock breaking [2, 3]. Yang *et al.* [4] investigated the uniaxial compressive properties of deep sandstone under microwave treatment, showing that the primary cause of thermal stress is the uneven expansion of minerals at the microscale. A similar conclusion was reached by Gao *et al.* [5]

Due to the complexity and variability of the electromagnetic field, the microwave effect can be significantly influenced by the irradiation direction for identical samples [4]. Pressacco *et al.* [6] confirmed that microwave direction can affect electromagnetic field distribution. The Brazilian disc test is a widely used method for investigating the tensile strength and behavior of samples [7]. Zhou *et al.* [8] and Du *et al.* [9] investigated the tensile properties and failure modes of granite and coal using Brazilian disks, respectively. Few studies have addressed the effect of microwave irradiation direction on the basic mechanical properties of standard rock samples.

Therefore, it is essential to investigate the tensile properties of disc rock samples under different microwave irradiation directions. In this study, granite, a common heterogeneous hard rock, is selected as the research subject, with a focus on the influence of different micro-

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wave irradiation directions. A continuous-discrete method is applied to analyze the tensile failure of granite samples treated by microwave. Subsequently, the electric field, temperature field, thermal damage, and tensile failure behavior are investigated. The results may offer valuable references for the microwave-treated Brazilian disc test.

Establishment of the numerical model

Methodology of model

The finite element method has limitations in simulating the failure behavior of rock. While the discrete element method excels at simulating fracture characteristics, it cannot calculate the electromagnetic field [10]. Therefore, combining continuous microwave electromagnetic calculations with discrete element thermal-mechanical calculations is a viable method for simulating the tensile behavior of microwave-treated granite samples. To achieve this, an electromagnetic-thermal coupling model was developed in COMSOL Multiphysics. The temperature field of the granite samples under different microwave irradiation conditions was then obtained. Based on the ball distribution of the discrete element model, the temperature field data of the samples were interpolated and imported into the discrete model. Finally, a thermal-mechanical coupling discrete element calculation was completed to capture the mechanical properties and fracture behavior of microwave-treated granite samples.

Model of electromagnetic-thermal coupling

In this study, the microwave irradiation model is based on the self-developed microwave-assisted rock breaking system. The microwave irradiation cavity is cubic, with sides measuring 400 mm, and the waveguides are arranged vertically at the centers of two opposing sides of the cavity. The BJ-26 waveguide (86.4 mm × 43.2 mm × 100 mm) is used, with the microwave frequency set to 2.45 GHz. Based on previous studies of granite samples under microwave irradiation, the microwave energy input is set to 3 kW for 60 seconds in this study, considering the microwave effect and sample fracture conditions.

This study aims to investigate the effects of microwave irradiation on the tensile behavior of granite in the Brazilian disc test under different irradiation directions. Thus, the gran-

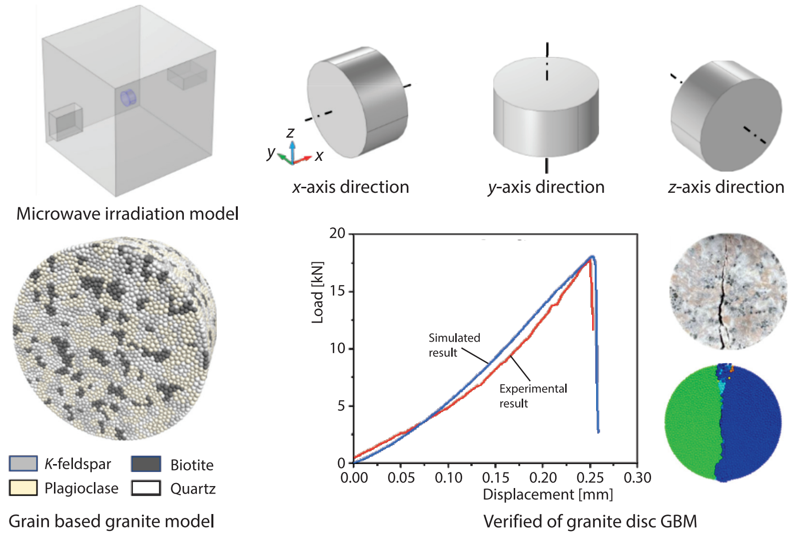

Figure 1. Continuous microwave irradiation mode and discrete element granite model

ite sample is prepared as a disc with a diameter of 50 mm and a height of 25 mm. Additionally, three orientations are considered, with the disc axis aligned parallel to the *x*-, *y*-, and *z*-axes, while the center of the sample remains stationary, as shown in fig. 1.

Thermal-mechanical coupling in discrete element model

To reflect the heterogeneous mineral composition of granite, the granite disc sample (∅50 mm × 25 mm) in the discrete element method is established using the grain-based model (GBM). One granite disc GBM contains 58519 particles, 323365 contacts and 7586 clusters. Based on the mineral composition of granite from a previous study [8], the model is composed of approximately 25% quartz, 39.4% plagioclase, 22% *K*-feldspar, and 13.6% biotite, fig. 1. Different mineral particles have distinct contact and thermal parameters to accurately simulate the mechanical behavior of real granite. The Brazilian splitting test results for the granite model were validated by experimental results. Figure 1 shows a comparison between the experimental and simulated results. It is evident that the load-displacement curve and fracture mode show minimal differences between the simulated and experimental results, demonstrating the high reliability of the granite GBM in this study.

Results of the microwave irradiation simulation

Electric field and temperature field

Figure 2 shows the electric and temperature fields of the granite disc sample after 60 seconds of microwave irradiation at 3 kW in different directions. It is evident that there is little difference in the overall electric field distribution of the model. The influence of different disc axis directions is minimal, likely due to the small size of the disc sample relative to the overall cavity. The highest electric field norm for all disc samples is located at the center, though the electric field distribution shows some differences. The sample axis in the *x*-axis direction shows the lowest maximum electric field norm, particularly in the case of the disc

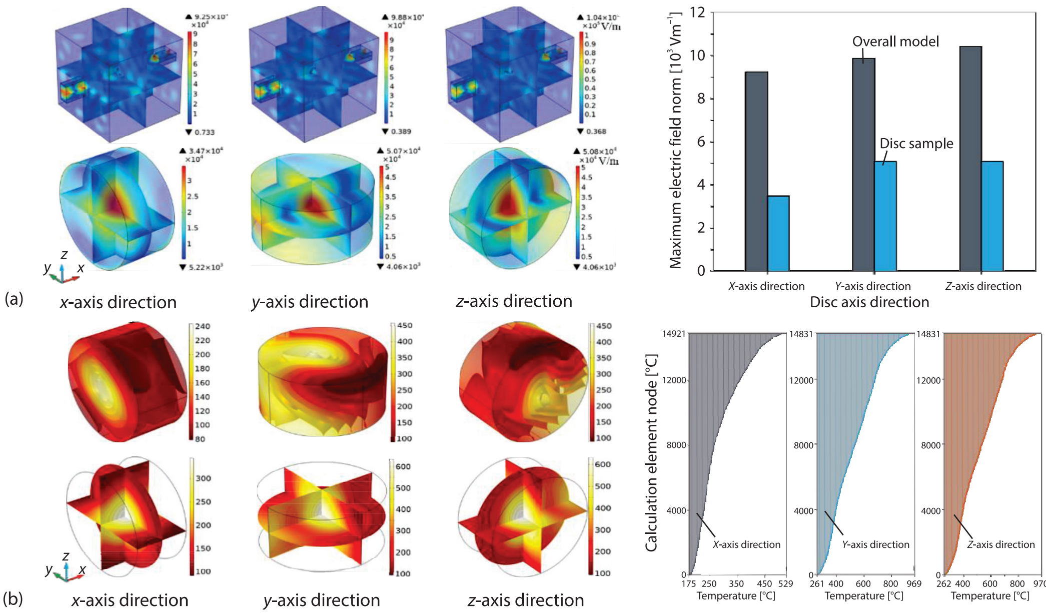

Figure 2. Calculation results of the electromagnetic-thermal coupling model simulation

sample The maximum electric field norm of the sample in the y-axis and z-axis directions is nearly identical, at 147% of that in the x-axis direction. Thus, it can be concluded that the disc axis orientation influences the electric field of the sample, particularly in the x-axis direction, ultimately leading to significant differences in temperature rise.

The temperature field of the sample closely mirrors the electric field, due to the microwave energy absorbed by the dielectric material, which causes a temperature increase. The temperature field of the sample in the x-axis direction shows significant symmetry. The high temperature area is concentrated near the sample's axis, with the highest temperature located very close to the geometric center of the sample. The temperature fields of the sample in the y-axis and z-axis directions are similar. High temperatures exceeding 300 °C appear not only near the sample's axis but also at the edges of the disc.

The temperature of calculation element nodes of sample in different direction condition have counted and sorted. In accordance with the temperature field distribution, the temperature values of the sample in the y-axis and z-axis directions are similar and significantly different from those in the x-axis direction. The highest temperature of the sample in the x-axis direction is 529 °C, which is almost half that of the other two conditions. Additionally, the temperature range of the sample in the x-axis direction is 354 °C, significantly lower than the 708 °C observed in the other two conditions, which can result in reduced thermal stress in the sample. It is worth noting that the curve for the x-axis direction is relatively steeper than those of the other two conditions, due to the greater symmetry of the sample in the x-axis direction, where the high temperature area is concentrated near the sample's axis.

Fracture behavior

The thermal-mechanical calculation results of granite disc sample after microwave irradiation are presented in fig. 3. The microwave colors cyan, blue, red and green correspond to inter-grain shear microcracks (ESC), inter-grain tensile microcracks (ETC), intra-grain shear microcracks (ASC), and intra-grain tensile microcracks (ATC), respectively. The total number of microcracks in the x-axis direction is 18, significantly fewer than in the other two conditions, which is attributed to the lower temperature field. The centers of the samples in all conditions exhibit a distribution of microcracks, which primarily occur in areas with temperatures exceeding 500 °C. From the statistics of the number of microcracks in different types, it is evident that tensile failure is the primary failure mode of granite after microwave irradiation. Furthermore, the number of inter-grain microcracks is almost twice that of intra-grain microcracks, which is due to the relatively weak strength of grain cementation. Similar phenomenon can be observed in other experimental research [11].

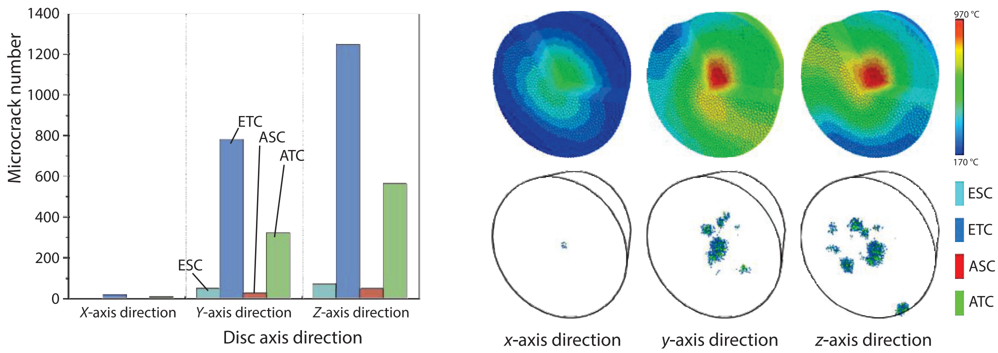

Figure 3. Thermal-mechanical results of the granite samples after microwave irradiation

Results of the Brazilian disc test after microwave irradiation

Tensile failure behavior

The force-displacement curve of the sample in the x-axis direction shows little difference from that of the untreated sample, particularly in the pre-peak stage. The damage caused by microwave irradiation in the x-axis direction is insufficient to influence the tensile failure behavior of the sample. The peak loads of the samples in the y-axis and z-axis directions are reduced by 13.84% and 10.05%, respectively, compared to those of the untreated sample. Based on the microcrack composition, this reduction can be attributed to the thermal damage caused by microwave irradiation at the center of the samples, which effectively decreases the tensile strength of the disc samples. It is worth noting that the pre-peak stage of the sample in the z-axis direction differs from that of the untreated sample. This phenomenon is caused by the greater number of microcracks in the sample under z-axis directional conditions, ultimately leading to microdestruction of the sample during initial loading.

Fracture characteristic

Figure 4 illustrates the final failure results in the form of ball fragment and distribution of microcracks. It is evident that the main fracture regions of the samples in the y-axis and z-axis directions are more extensively damaged, which proves that microwave irradiation effectively influences the tensile strength of the disc samples. Moreover, the greater the thermal damage in the main fracture regions, the more pronounced the decrease in the tensile strength of the samples after microwave treatment. In all conditions, tensile failure is the primary failure mode of the samples in the Brazilian disc test, while shear microcracks primarily occur near the loading plate. It can be concluded that microwave irradiation, which does not directly destroy the bearing structure of the specimen, has little effect on the tensile fracture characteristics of the sample.

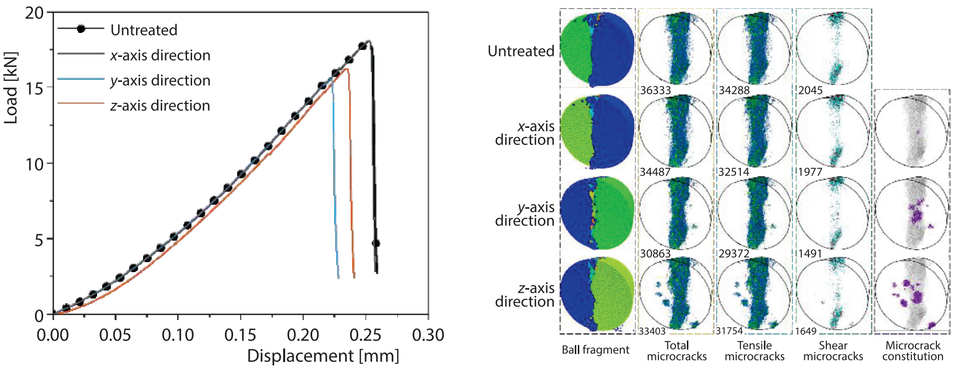

Figure 4. Brazilian disc test results of samples after microwave irradiation

Conclusions

The direction of microwave irradiation has minimal influence on the electric field of the overall model. This is attributed to the relatively small size of the disc sample compared to the overall cavity. The electric and temperature field of disc samples exhibit significant differences under varying directional conditions. The influence of microwave treatment on the tensile failure behavior of the disc samples depends on the degree of thermal damage caused by microwave irradiation in the main fracture region during the Brazilian disc test.

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