Thermal stresses and temperature distribution of granite under microwave treatment

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Abstract. Efficient breakage of high strength rocks is a challenging task where conventional drilling and blasting methods are not preferred or allowed, for example, rock excavation in long tunnels at a great depth and urban environment sensitive to noise and vibration. Microwave treatment is an efficient and environmentally friendly method, which is considered to be one of the most promising ways to increase the performance of mechanical excavators, such as roadheaders and impact hammers. However, the mechanisms of microwave fracturing of granitic rocks have not been well investigated. In this study, Chinese granite was used as the research material. Its mineral composition and grain size were first characterized using petrographic thin section observation. Cubic granite samples were then heated in a single-mode industrial microwave. The temperature was captured using a high resolution infrared thermal camera. Then a realistic 3-D rock model with the same mineralogical properties was established using Voronoi tessellation. The multi-physics numerical model was calibrated using data from microwave heating tests. The effect of microwave power intensity, heating time, and mineral grain size on the temporal and spatial temperature distribution, and thermal stresses in the granite matrix was investigated in a comprehensive manner. The temperature gradients and thermal stresses were calculated. The maximum temperature gradient and the maximum tensile stress appeared at the interface between quartz and biotite. As either power level or heating time increased, the thermal gradient and the maximum tensile stress increased, and with same microwave energy output, greater temperature gradient and thermal stress could be generated during microwave heating at higher power levels for shorter durations. Moreover, the greater the grain size, the bigger the maximum tensile stress. The finding of the paper contributes the understanding of the mechanisms of microwave fracturing of rocks.

Keywords: Microwave treatment, Thermal stress, Temperature distribution, Grain size
1 Introduction

Rock fragmentation is a fundamental process in the fields of tunneling and mining engineering, slope engineering, and energy engineering (Flegner et al., 2014). The traditional approach of rock disintegration can be categorized in two groups: mechanical fracturing and blasting fracturing, which account for more than 90% of the task. Drilling and blasting method has unparalleled advantages in large-scale rock engineering but the shortcomings of low configuration precision and support difficulty limit the application of this method to some extent. Mechanical rock fracturing method, the most economical and the most commonly used one, has been developed rapidly in the last century due to several advantages over drilling and blasting method, including continuous operation, minimum ground disturbance, safer and more environmental-friendly operation, and higher excavation rate in favorable ground conditions (Hassani et al., 2016; Shepel et al., 2018). However, the excavation and performance of mechanical equipment, such as tunnel boring machines could be greatly compromised by the low penetration rate, low advance rate, and excessive cutter wear, when encountering hard rock, especially extremely hard rock (Wang et al., 2015; Zheng et al., 2016).

Rock fragmentation has become one of the bottlenecks restricting abrasive rock geotechnical engineering and many scientists have been seeking more economical and efficient methods for rock breaking, including abrasive water jet (Liu et al., 2019), laser breaking (Graves et al., 2000), infrared irradiation (Barreiro et al., 2019), and microwave heating method (Ma et al., 2021). Owing to several advantages, microwave heating technology has provided a new research direction and garnered immense interest for rock breaking and fracturing (Lu et al., 2019a; Lu et al., 2019b; Wei et al., 2019; Zheng et al., 2020; Zheng et al., 2017).

Microwave heating rock is driven by the absorption of microwaves by the rock, leading to the conversion of the electromagnetic energy into heat. Rock is composed of different minerals with different dielectric and thermodynamic properties, such as specific heat capacity, thermal expansion, and thermal conductivity (Fan et al., 2018), resulting in different responses to the microwave irradiation. Therefore, mineral particles produce variable volume expansions and heating reactions under microwave irradiation. The structural thermal stress induced by thermal mismatch and thermal gradient causes the expansion of existing cracks in the rocks and produces a large number of new micro- and macro-cracks, negatively affecting the physical and mechanical properties (Li et al., 2019; Nelson and Trabelsi, 2012; Toifl et al., 2017; Wang and Djordjevic, 2014; Whittles et al., 2003).

The microwave rock breakage technique was first introduced in the 1960s, and the previous study indicated that rock breaking has technical and economic feasibility (Zheng et al., 2021a). Since then,
various research methods, including laboratory tests and numerical simulations have been widely used to study the effect of microwave heating on physical and mechanical properties of rocks.

With the development of computer simulation technology, the numerical simulation of microwave heating of rock can provide the stress distribution, internal temperature, and other parameters that cannot be obtained via experiments. It can efficiently analyse the failure of crystal grain boundaries under microwave irradiation, helpful in identifying the mechanism of resulting rock damage and failure. Table 1 lists the summary of numerical studies on microwave treatment of rocks. The reactions of various rocks to microwave irradiation have been studied at different power levels, for different exposure times, and in different cavity modes (single-mode and multi-mode).

Table 1 Summary of the numerical studies on microwave treatment of rocks

| Method | Software | Model | Influencing factors | Parameters studied | Findings | References |
|--------|----------|-------|---------------------|--------------------|----------|------------|
| Finite difference Method | FLAC | 2D model of a simplified pyrite/calcite system | Power density, Heating time | UCS | High power density is more economically viable for microwave fracturing rock | (Whittles et al., 2003) |
| Finite difference Method | FLAC | 2D model of a simplified pyrite/calcite system | Microwave power density, Exposure time | UCS | High power density combined with a short heating interval is expected to offer the best energy efficiency | (Jones et al., 2005, 2007) |
| Finite difference time domain-Finite element | Meep-Abaqus | Three-component-granite model | Power density, Heating time | Temperature field, Thermal stress | The maximum temperature and the largest maximum stress increase linearly with the irradiation time. | (Toifl et al., 2017; Toifl et al., 2016) |
| Finite element Method | ANSYS | Thermal-based particle modelling of different calcite/pyrite ratios | Calcite/pyrite ratios, Power density, Exposure time | Temperature field, Fracture density | Increasing the power density and the mixture ratio of pyrite/calcite, a high grinding efficiency of ore can be reached | (Wang et al., 2008) |
| Finite element Method | ANSYS | A calcite matrix with one pyrite inclusion | Power density, Exposure time | Temperature profile, Maximum tensile stress, Principle stress | High power density combined with a short exposure time will get greater strength reduction | (Wang and Djordjevic, 2014) |
| Finite element Method | COMSOL Multiphysics | 2D model a realistic microstructure pegmatite | Heating time | Temperature field, Thermal stress | Thermally-induced compressive and tensile stresses increase as the microwave irradiation duration increases. | (Li et al., 2019) |
| Finite element Method | COMSOL Multiphysics | Coal | Microwave frequency, Microwave power, sample position | Temperature profile, electric field distribution | Lower power microwave-treatments required more energy than microwave treatment with higher power when heating temperature greater than 200°C | (Hong et al., 2016) |
| Finite element Method | ABAQUS | Basalt | Power density, Heating time | Thermal stress, temperature gradient | The onset of damage and formation of cracks in rock samples with dimensions of the order of the temperature gradients developing under microwave irradiation | (Hartlieb et al., 2012) |
| Discrete element method | PFC | Two-phase conceptual ores | Power density, Grain size | The number of micro-cracks, | High power pulsed equipment would be more efficient than continuous wave equipment for treating fine-grained ores | (Ali and Bradshaw, 2009, 2010, 2011) |

The numerical simulations listed above have promoted the research on the fundamental mechanism and characteristics of microwave-induced rock heating. Nevertheless, the existing research still lacks the understanding of the influence of mineral grain size on rock stress and temperature distribution.
Therefore, the objective of this study is to quantitatively investigate thermal stresses and temperature distribution of granite under microwave treatment. Firstly, the mineral composition and grain size of granite were characterized using petrographic thin section observation. Then, the cubic granite samples were heated in a single-mode industrial microwave. Then, a realistic 3-D rock model with the same mineralogical properties was established using Voronoi tessellation and calibrated using data from microwave heating tests. Finally, the effect of microwave power intensity, heating time, and mineral grain size on the temporal and spatial temperature distribution and thermal stresses in the granite matrix was investigated comprehensively.

2 Experimental study

2.1 Materials

The rock samples in the present study were collected from a quarry in Fujian province, China. Figure 1 shows the optical image and the cross-polarized light (XPL) micrograph of a petrographic thin section. It is seen from Figure 1 that the granite sample consisted mainly of 46% alkali feldspar, 7% biotite, 42% quartz, and 5% plagioclase. The average grain size was about 6.5 mm. Cubic specimens of 40 mm × 40 mm × 80 mm were prepared and used in the tests. The P-wave velocity and density of the specimens were measured, and the specimens with consistent P-wave velocities and no visible cracks were selected for the experimental tests.

Figure 1. Optical image and petrographic microscopy image of the rock under XPL (Bt-biotite; Afs-alkali feldspar; Pl-plagioclase; Qtz-quartz)

2.2 Experimental equipment

A 2.45 GHz single-mode industrial microwave system (Model: Sairem G4) with maximum power of 6 kW was used in the microwave heating tests (Figure 2). The components and functions of the microwave source are mentioned in previous studies Zheng et al. (2017) and Zheng et al. (2021b). After the heating test, the applicator was opened immediately, and the surface temperature of the
specimens placed in the WR340 waveguide were captured by an infrared camera (model: FLIR T420) with a measurement range of −20°C–650°C. The thermal camera had two measurement ranges (−20°C–120°C, 100°C–650°C) and the range was preset according to the trial tests to obtain more accurate results.

Figure 2. The experiment setup of the microwave treatment of rocks

2.3 Experimental results

The relationship between the maximum temperature and the power is shown in Figure 3. It can be seen from the figure that the maximum temperature increased as the power increased. At the beginning, the maximum temperature increased linearly with the power level from 1 kW to 4 kW at a steady rate. Then, the maximum temperature was slightly increased from 175°C to 205°C at 4–5 kW. After that, the maximum temperature increased sharply, reaching nearly 280°C at 6 kW.

Figure 3. The relationship between the maximum temperature and power
3 Numerical model

As shown in Figure 4, a realistic 3-D rock model composed of different mineral grains was established using the Voronoi tessellation method. Of these grains, the red grains were alkali feldspar, the white grains were quartz, the black grains were biotite, and the gray grains were plagioclase. The proportions of various minerals and average grain size in the numerical model were consistent with the results obtained from the thin section. The average grain size was about 6.5 mm. It should be noted that the preexisting cleavages and cracks in the rock were not considered in this study. The rock sample of 40 mm × 40 mm × 80 mm was placed in the WR340 waveguide. A water load at the end of the circuit was used to absorb the energy transmitted through the specimen, which simulated the field scenario and prevented the microwave leakage. The diameter of the water pipe was 25 mm and the water flow speed was 0.3 m/s. The parameters of the rock-forming minerals are shown in Table 2. The convection heat exchange coefficient between rock and air was 5 W/(m²•K).

| Parameters                | Alkali feldspar | Biotite | Plagioclase | Quartz   |
|---------------------------|-----------------|---------|-------------|----------|
| Coefficient of thermal expansion | 3.6e6           | 3e-6    | 3.7e-6      | 1.21e5   | 1/K      |

Figure 4. A realistic 3-D rock model with the same mineralogical properties (500 grains, the red grains are alkali feldspar, the white grains are quartz, the black grains are biotite, and the gray grains are plagioclase).

In the simulation, the microwave power levels at the port were 1, 3, and 6 kW, respectively; they operated in the TE10 mode with the exposure time of 1 min. The metallic waveguide and cavity walls were considered as the perfect electric conductors.
| Property               | Value 1 | Value 2 | Value 3 | Value 4 |
|-----------------------|---------|---------|---------|---------|
| Heat capacity         | 757     | 770     | 808     | 730     |
| Density               | 2570    | 3020    | 2760    | 2650    |
| Thermal conductivity  | 2       | 1.95    | 2       | 6.5     |
| Young’s modulus       | 87e9    | 33.8e9  | 87e9    | 95e9    |
| Poisson’s ratio       | 0.29    | 0.27    | 0.29    | 0.17    |
| Relative permittivity | 5.55    | 7.48    | 5.62    | 4.7     |
| Loss tangent          | 4.7e-5  | 3e-2    | 3e-3    | 1.88e-4 |

4 Numerical results

The multi-physics numerical model was calibrated using data from the microwave heating tests. Figure 5 shows the simulated maximum temperature of granite treated by microwave. The results show that the numerical results are similar to the experimental results, verifying the accuracy of the numerical models and parameters of the rock-forming minerals in the numerical simulations.

5 Discussion

5.1 Stress distribution

Figure 6 shows the maximum principal stress distribution of rock sample treated at 6 kW for 1 min along the line. The results show that the maximum principal stress increased with the exposure time,
from 10 MPa in 10 s to 45 MPa in 60 s, and the largest first principal stress of 45 MPa appeared at the interface between biotite and quartz.

**Figure 6.** The stress distribution of the rock sample treated at 6 kW for 1 min along the center line (marked in red)

**Figure 7** shows the maximum principal stress treated at 1 kW and 3 kW for 1 min. The results show that the higher the microwave power, the greater the maximum principal stress. The maximum principal stress increased from 5 MPa at 1 kW to 45 MPa at 6 kW. And it is obvious that the longer the exposure time, the greater the maximum principal stress.

**Figure 7.** The maximum principal stress treated at (a) 1 kW and (b) 3 kW for 1 min
5.2 Temperature gradient

Figure 8 shows the temperature gradients of the rock sample treated at 1 kW, 3 kW, and 6 kW for 1 min along the line. The results show that the maximum temperature gradient appeared at the interface between quartz and biotite. With the increase in the microwave power, the maximum temperature gradient increased. It should be noted that with same microwave energy output, greater temperature gradient and thermal stress could be generated during microwave heating at higher power levels for shorter durations.

Figure 8. The temperature gradients of the rock sample treated by (a) 1 kW, (b) 3 kW, and (c) 6 kW for 1 min along the line

5.3 The relationship between thermal stress and grain size

In this study, two different grain sizes of 100 and 500 grains were tested. The microwave power was 6 kW and the exposure time was 1 min. Figure 9 shows the maximum principal stress of two models with different grain sizes. The results show that the greater the grain size, the bigger the maximum tensile stress.
6 Conclusion

In this study, a realistic 3-D rock model composed of different rock-forming minerals was established using Voronoi tessellation and calibrated using data from microwave heating tests. The effect of microwave power intensity, heating time, and mineral grain size on the temporal and spatial temperature distribution and thermal stresses in the granite matrix was investigated in a comprehensive manner. The temperature gradient and thermal stresses were calculated. The simulation results show that the maximum temperature gradient and the maximum tensile stress appeared at the interface between quartz and biotite. With the increase in either power level or heating time increased, the thermal gradient and the maximum tensile stress increased, and with same microwave energy output, larger temperature gradient and larger thermal stress could be generated during microwave heating at higher power levels for shorter durations. The influence of grain size on the tension stress was also investigated. The results showed that the greater the grain size, the larger the maximum tensile stress.

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Conflict of interest statement

The authors declare no conflict of interest.
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