# EXPERIMENTAL OBSERVATION ON ROCK DAMAGE UNDER MICROWAVE THERMAL SHOCK

by

***Teng TENG***[a,b*]***, Peng YI***[a]***, Wen-Jian JIA***[a]***, and Xiao-Yan WU***[a]

[a] School of Energy and Mining Engineering,
China University of Mining and Technology Beijing, Beijing, China
[b] State Key Laboratory Cultivation Base for Gas Geology and Gas Control,
Henan Polytechnic University, Jiaozuo, China
[c] Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources,
China University of Mining and Technology-Beijing, Beijing, China

Original scientific paper
https://doi.org/10.2298/TSCI2404457T

*Microwave thermal shock is an optimized means of crushing rocks in engineering, in order to investigate the effect of microwave thermal shock on granite, this paper adopts microwave irradiation and SEM experiments to investigate the mechanical behavior and microstructural evolution law of granite, and the main conclusions are: With the increase of the duration of thermal shock, granite exhibits the law of linear increase, and the peak strength and elastic modulus show the trend of rising first and then decreasing; After thermal shock the acoustic emission signal of granite is linearly rising, while the internal shear cracks expand to form larger transgranular cracks, the results of the study have great significance for the future development of traditional mining technology.*

Key words: *heat shock, thermal damage, microwave, hard and brittle granite*

## Introduction

Microwave thermal shock has a great impact on the mechanical properties of rocks, and can even cause cracks and direct rock damage [1, 2]. Dai *et al.* [3] found that microwave can effectively reduce the strength of granite based on the experiment. Olubambi *et al.* [4] based on the study of sulfide minerals irradiated by microwave, found that the change of internal damage in rocks was related to the depth of microwave penetration in a specific direction. Hartlieb *et al.* [5] substituted the test data into numerical simulation. The evolution mechanism of basalt tensile strength and internal crack generation under 3.2 kW microwave power is studied. After the test, Hassani *et al.* [6] found that among different types of rock samples, the uniaxial compressive strength of basalt was the most significantly decreased after microwave irradiation, and thermal cracking was found on the surface of the sample. Reinosa *et al.* [7] found through experiments that when the furnace temperature exceeds 650 °C, the heating rate of kaolin is further increased, and its heating rate is related to the resistivity to a certain extent. Whittlest *et al.* [8] believe that under the action of microwave irradiation, wave-absorbing mineral particles in rock mass absorb microwave energy and form *hot spots* in rock mass. Kingman *et al.* [9, 10] built a 2-D model and used high energy microwave irradiation analyze the intensity changes of mineral particles before and after microwave irradiation. Teng *et al.* [11, 12] carried out microwave thermal shock and uniaxial compression tests on typical hard brittle sand-

* Corresponding author, e-mail: t.teng@cumtb.edu.cn

stonewith a strong bursting liability, and analyzed the physical and mechanical properties of sandstone and the response law of bursting liability indicators after microwave thermal shock.

This paper implemented a series of microwave thermal shock and mechanical tests have been conducted to observe the deterioration of the mechanical properties of granite and the crack evolution mechanism. The research results can provide reference for the development of microwave mining technology and microwave rock breaking engineering.

## Experiment process

The hard granite in Suizhou, Hubei province, was selected as the test object. The surface was smooth and there were no visible joint cracks. In the natural state, the uniaxial compressive strength of the specimen is 60-100 MPa, and the failure deformation is less than 3%. According to the ISRM recommended standard, the sample was processed into a standard cylinder sample with a diameter of 50 mm and a height of 100 mm, as shown in fig. 1(a).

The test equipment used in the test of hard and brittle granite under microwave heat mainly includes high precision program-controlled microwave generator for microwave heating, Thermal Infrared Sensitive Imaging System for temperature monitoring, Electronic Universal Testing Machine for mechanical property test, and Multi-Channel Acoustic Emission Meter for monitoring the acoustic emission energy during the damage of rock samples. We now consider the PCI-Express 8 multi-channel acoustic emission meter for acoustic emission energy monitoring of damage processes in rock samples, as shown in fig. 1(c).

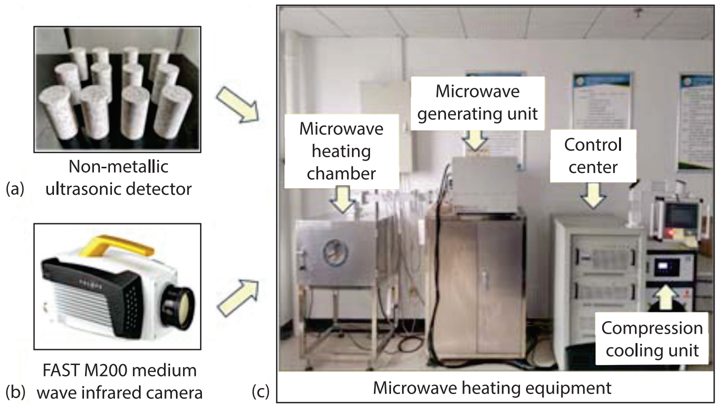


**Figure 1. Microwave experimental equipment diagram**

The selected rock samples were divided into 6 groups, and each group of test conditions was repeated for three times. Before microwave irradiation, the non-metallic ultrasonic monitoring instrument ZBL-U510 was used to measure the wave velocity of rock samples. Then the rock samples were soaked for 48 hours to restore the original rock saturated state.

The microwave power used for thermal shock treatment is 4 kW, and the corresponding time of each group is 0 second, 60 seconds, 120 seconds, 180 seconds, 240 seconds, and 360 seconds, respectively, and repeated for three times. An observation window is provided in the microwave heating chamber for the thermal infrared sensitive imaging system to display the surface thermal signal of the sample under microwave thermal shock. Based on the thermal signal, the surface temperature of the rock under different thermal shock duration was recorded, and the temperature change curve was drawn, as shown in fig. 2. As can be seen from the figure, the thermal shock duration plays a decisive role in the change of rock surface temperature, and the surface temperature increases with the extension of microwave irradiation duration. Before 120 seconds, the surface temperature presents a slight upward trend, and the heating rate is 0.72 °C per second at the maximum; during 120-180 seconds, the heating rate increases abruptly, reaching 1.27 °C per second.

After the microwave thermal shock, the sample was naturally cooled to room temperature, and the wave velocity test was carried out again, and the uniaxial compression acoustic emission test was carried out using the MTS e45.305 electronic universal testing machine.

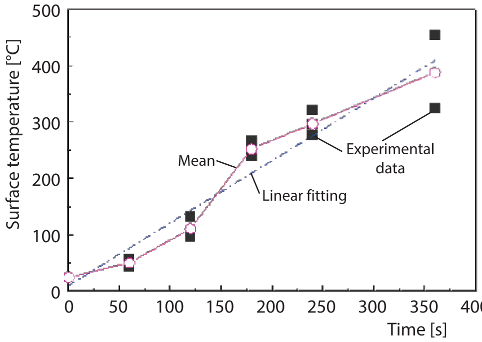


**Figure 2. Rock sample heating rate curve graph**

## Results and discussions

### *Wave velocity change*

Figure 3 shows the change curve of wave velocity before and after microwave thermal shock of granite. By comparing the two curves in fig. 3, it can be seen that both curves show a downward trend with the extension of irradiation time. The difference is that the curve before thermal shock tends to be flat and slightly decreases, while the curve after thermal shock significantly decreases. Specifically, the duration is between 0-60 seconds and 120-180 seconds, and the decline rate gradually decreases after 180 seconds. The reason is that the rock sample is in a water-saturated state before being put into the metal cavity, and the microwave thermal shock causes the rock to heat up, and the water in the pore layer and the bound water in the specimen escape, and the wave velocity decreases.

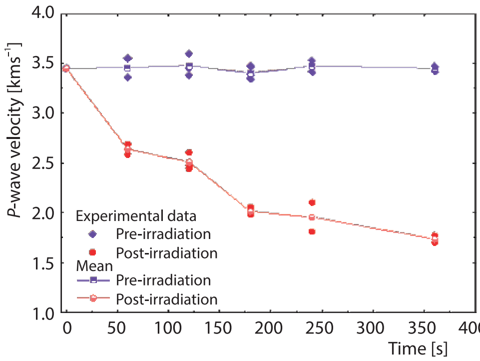


**Figure 3. Wave velocity variation of granite samples**

### *Microscopic crack structure*

The VEGA SEM was used to make a comparative analysis of the surface pore structure of the granite specimen in the natural state and 360 seconds after microwave thermal shock. The results as shown in fig. 4 show that the granite diagenetic minerals in the natural state have obvious plat structure accompanied by subtle primary cracks of different types, the width of which is about 0.5-1.5 μm. Most of them are more than 50 μm in length, and the intergranular crack in fig. 4(a) even exceeds 350 μm in length.

After 360 seconds of 4 kW microwave thermal shock, the transgranular crack on the surface of the sample in fig. 4(b) expanded into a large crack with a width of about 10 μm. Shear slip failure occurred on the surface of the crack, and a new intergranular crack appeared on the end face in the shape of cleavage step. Under a lens of 3000×, the grain surface in fig. 4(b) is sharper than that in fig. 4(a), showing a knife-like appearance, while the crack surface in fig. 4(a) is relatively smooth, and there are fleecy materials on the surface of the plate-like structure. Combined with the macroscopic microwave irradiation test, it can be preliminarily speculated that the granite is subjected to uneven heat after microwave thermal impact, resulting in the gradual formation of internal temperature gradient. The primary crack is directly affected by the temperature gradient and expands to form shear crack, and then continues to expand to form transgranular crack, which directly causes macroscopic fracture of the granite.

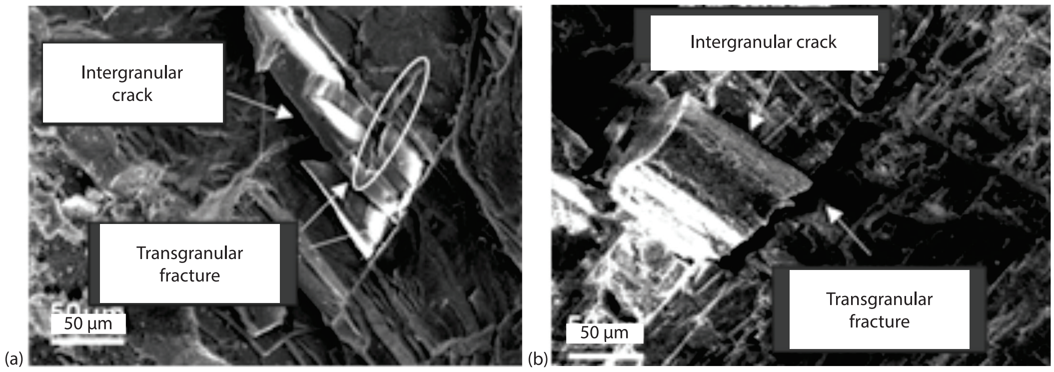


**Figure 4. The SEM results of granite; (a) natual state and (b) microwave irradiate 360 seconds**

## *Mechanical parameters*

According to the stress-strain data of granite after experimental, the data of peak stress, $\sigma_p$, and elastic modulus, $E$, of granite under different irradiation duration were extracted and analyzed, and the data were fitted, as shown in fig. 5. By comparing the change curves of peak stress and elastic modulus in fig. 5, it can be seen that the trend of the change curves is generally the same, showing a gentle rise at first, then a rapid rise and then a sudden decline in general. The fitted curve and irradiation duration meet the sine function curve relationship. The elastic modulus of the sample showed a gentle upward trend. During the stage of 120-180 seconds, the peak stress and elastic modulus of the granite increased rapidly, reaching the maximum values of 134.79 MPa and 7.5940 GPa in the test, which increased by 98.94% and 12.55% compared with the control group without microwave irradiation. After 240 seconds, the elastic modulus of granite samples began to show a rapid decline trend.

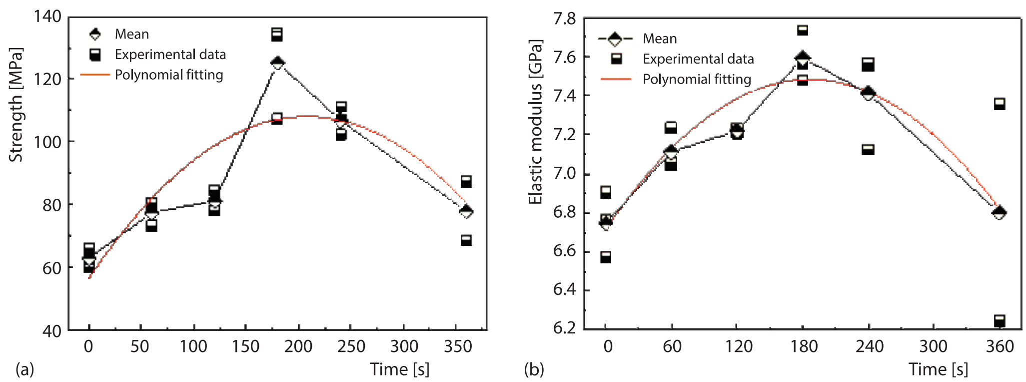


**Figure 5. Change curves after microwave irradiation;**
**(a) changes in granite peak strength and (b) changes in elastic modulus**

Figure 6 shows the variation of acoustic emission energy released during uniaxial compression of rock samples under different irradiation duration. At the initial stage of loading, compared with the rock samples without microwave thermal shock, the rock samples treated with different irradiation duration were more active in this process, and the acoustic emission signals also increased more, among which the ringing counts with irradiation duration of 240 seconds showed one or more peaks.

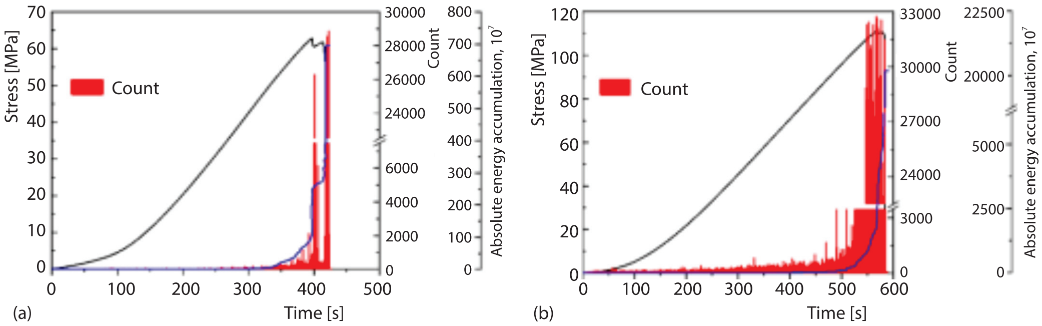


**Figure 6. Partial granite time-stress-ring count-absolute energy accumulation curve; (a) $t = 0$ second and (b) $t = 240$ seconds**

## Damage constitutive model of hard granite

In the aforementioned tests in this paper, the damage source of granite samples is mainly uniaxial compression after thermal stress generated by microwave thermal shock. Therefore, the maximum compressive stress criterion is adopted in this paper to determine the failure mode expression of the material:

$$F_c \equiv \sigma_c - f_{c0} = 0 \tag{1}$$

where $f_{c0}$ is the uniaxial compressive strength and $F_c$ – the damage threshold function characterizing compressive damage.

According to the experimental results, as the end pressure gradually increases, $F_c$ is starting from 0 and slowly increasing until it exceeds $f_{c0}$, the rock sample enters the plastic stage. Throughout this process, internal damage in the rock sample continues to grow. Simultaneously, the elastic modulus $E$ of the rock sample exhibits a monotonous decrease as the damage variable $D$ increases. The mathematical relationship is expressed:

$$E = (1 - D)E_0 \tag{2}$$

A power function is employed to characterize the softening proces 3 seconds of the rock specimens after reaching the peak strength. The damage variable $D$ is defined:

$$D = \begin{cases} 0 & \varepsilon \le \varepsilon_{c0} \\ 1 - \left|\dfrac{\varepsilon_{c0}}{\varepsilon}\right|^n & \varepsilon_{c0} \le \varepsilon \le \varepsilon_{cr} \\ 1 - \left|\dfrac{\lambda_c \varepsilon_{c0}}{\varepsilon}\right|^n & \varepsilon_{cr} \le \varepsilon \le \varepsilon_{cu} \\ 1 & \varepsilon_{cu} \le \varepsilon \end{cases} \tag{3}$$

where $D$ is the damage variable under the combined influence of uniaxial compression and thermal stress, $E_0$ – the elastic modulus of the rock sample in its intact state, $\varepsilon_{c0}$ – the compressive strain at the limit of the elastic stage for the rock sample, $\varepsilon_{cr}$ – the compressive strain at which the rock sample enters the plastic stage and reaches residual strength, $\varepsilon_{cu}$ – the ultimate strain of the rock sample, and $n$ – the constitutive coefficient, set to 2 in this paper.

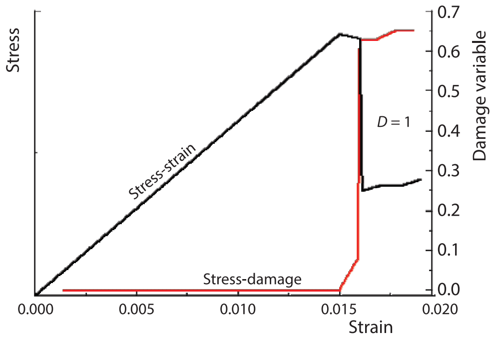


**Figure 7. Rock stress-strain-damage function relationship graph**

As the temperature within the hard rock mass continues to rise, thermal stress develops within the rock mass. Under the influence of thermal stress, deformation occurs in the rock samples. Due to volume strain $\varepsilon$ controlling the damage variable $D$, and $D$ influencing the Young's modulus, the rock undergoes changes. According to the aforementioned eq. (3), a stress-strain-damage function is established, as shown in fig. 7. When the volume strain $\varepsilon$ of the rock mass reaches 1.5%, the damage variable $D$ may have a sudden change, which is reaching 0.65. This is considered the strain limit for the rock, indicating failure has occurred.

## Conclusions

In this paper, through the experiments of microwave irradiation and physico-mechanics, using the macro and microscopic perspectives, the mechanical properties of granite are obtained with the change of microwave thermal shock time and the evolution of internal cracks, and the conclusions are as follows.

- The surface temperature increases with the prolongation of microwave irradiation time, the acoustic emission signal rises linearly, the uniaxial peak intensity and elastic modulus show a tendency to increase firstly and then decrease, and the wave speed is exponentially and significantly decrease;
- Compared with the sample without overheat impact, the surface crack expanded into a large crack of 10 μm, shear slip failure occurred on the crack surface, cleavage step fracture occurred on the end face, and a new intergranular crack appeared;
- With the increase of microwave impact duration, the internal thermal stress caused the rock samples to undergo expansion and deformation, and when the volumetric strain reached 1.5%, the damage mutated to 0.65 and the rock samples were damaged.

## Acknowledgment

The authors are grateful to the the Fundamental Research Funds for the Central Universities (2022JCCXNY06), and the National Key R&D Program of China (2022YFC3004602), and the National Training Program of Innovation and Entrepreneurship for Undergraduates (202411019).

## References

[1] De Silva, R. V., *et al.*, An Alternative to Conventional Rock Fragmentation Methods Using SCDA: A Review, *Energies*, *9* (2016), 11, pp. 10-27
[2] Chen, X., *et al.*, Determination of Mechanical, Flowability, and Microstructural Properties of Cemented Tailings Backfill Containing Rice Straw, *Construction and Building Materials*, *246* (2020), 1, 118520
[3] Dai J., *et al.*, Experimental Research on Reduction of Granite Strength Induced by Microwave Irradiation, *Proceedings*, World Mining Congress, Montreal, Canada, 2013
[4] Olubambi, P. A, *et al.*, Influence of Microwave Heating on the Processing and Dissolution Behaviour of Low-Grade Complex Sulphide Ores, *Hydrometallurgy*, *89* (2007), 1-2, pp. 127-135
[5] Hartlieb, P., *et al*., Damage of Basalt Induced by Microwave Irradiation, *Minerals Engineering*, *31* (2012), 3, pp. 82-89
[6] Hassani, F., *et al*., Microwave Assisted Mechanical Rock Breaking, *Proceedings*, 12$^{th}$ ISRM International Congress on Rock Mechanics, Beijing, China, 2011, pp. 2075-2080

[7] Reinosa, J. J., *et al*., A Step Ahead on Efficient Microwave Heating for Kaolinite, *Applied Clay Science*, *168* (2019), 2, pp. 237-243
[8] Whittles, D., *et al*., Application of Numerical Modelling for Prediction of the Influence of Power Density on Microwave-Assisted Breakage, *International Journal of Mineral Processing*, *68* (2003), 1-4, pp. 71-91
[9] Kingman, S., The Effect of Microwave Radiation on the Communication and Beneficiation of Minerals and Ores, University of Birmingham, Birmingham, UK, 1998
[10] Kingman, S., *et al*., The Influence of Mineralogy on Microwave Assisted Grindling, *Minerals Engineering*, *3* (2000), 2, pp. 313-327
[11] Teng, T., *et al.*, Experimental and Numerical Validation of an Effective Stress-Sensitive Permeability Model under Hydromechanical Interactions, *Transport in Porous Media*, *151* (2024), 2, pp. 449-467
[12] Teng, T., *et al.*, Experimental Investigation on the Evolution Law of Bursting Liability of Hard and Brittle Sandstone under Microwave Thermal Shock, *Journal of Mining Science and Technology*, *9* (2024), 2, pp. 209-216

Paper submitted: March 14, 2024
Paper revised: March 19, 2024
Paper accepted: May 10, 2024