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ORIGINAL PAPER

The Microwave-Induced Fracturing of Hard Rock

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Abstract

A new, high-efficiency technology for fracturing and breaking rocks is required. Due to various advantages including high efficiency, energy-saving, and having no secondary pollution, the technology of microwave-induced fracturing of hard rock has been considered as a potential method for rock fracturing and breaking. Aiming at the realisation of two engineering applications: microwave-assisted mechanical rock breaking and stress release from rock masses in deep underground engineering works to prevent geological disasters caused by high-stress concentrations such as rockbursts, a novel (open-type) microwave-induced fracturing apparatus (OMWFA) for fracturing hard rocks was developed. On this basis, the two modes of microwave-induced subsurface fracturing and microwave-induced borehole fracturing of hard rocks were proposed. Due to removal of the restraint of the microwave cavity, OMWFA can be used to fracture large-size rock samples and engineering-scale rock masses. Using the apparatus, the fracturing effects of the two fracturing modes on different dimensions of cuboidal basalt samples were investigated. By combining the microwave-induced fracturing apparatus with a press machine to explore the influence of unidirectional stress on the fracturing effect of microwave treatment on basalt. Moreover, field tests were carried out on rock masses encountered in underground engineering works at Baihetan Hydropower Station in Sichuan Province, China, and the fracturing effects were evaluated by applying a digital borehole televiewer and conducting acoustic wave testing. The results show that the apparatus had favourable fracturing effects on the subsurface and borehole samples of basalt. When no stress was applied, the cracks radially expanded from the approximate centre of the radiant surface and unidirectional stress promoted fracturing. The number and depth of cracks increased with prolonged microwave exposure. After microwave treatment, the P-wave velocity of the samples declined, and the longer the microwave exposure, the more significant the reduction in P-wave velocity was. The results of field test reveal that borehole fracturing can exhibit a favourable effect around boreholes. The sound velocity around the borehole and between the boreholes both declined to some extent. Microwave-induced hard rock fracturing offers guiding significance to those exploring and developing new rock breaking and tunnelling methods, and generally enhances construction safety in deep underground engineering works.

Keywords Microwave-induced fracturing of hard rock · Novel microwave-induced fracturing apparatus · Microwave-induced subsurface fracturing · Microwave-induced borehole fracturing · Microwave-assisted mechanical rock breaking · Stress release

List of Symbols

a, b, c, and *d*	Constants
w	Width of the cutter edge
D	Cutter diameter
L	Disc cutter rolling length
P	Penetration per revolution
CAI	Cerchar abrasivity index of the rock surface
F_n	Normal force applied by the disc cutter
σ_c	Uniaxial compressive strength
σ_τ	Direct shear strength
σ_{PTL}	Point load strength index
θ	One-half of the wedge-shaped disc cutter edge angle

1 Introduction

A new, high-efficiency technology for fracturing and breaking rocks is required in geotechnical and mining engineering. Due to various advantages including high efficiency,

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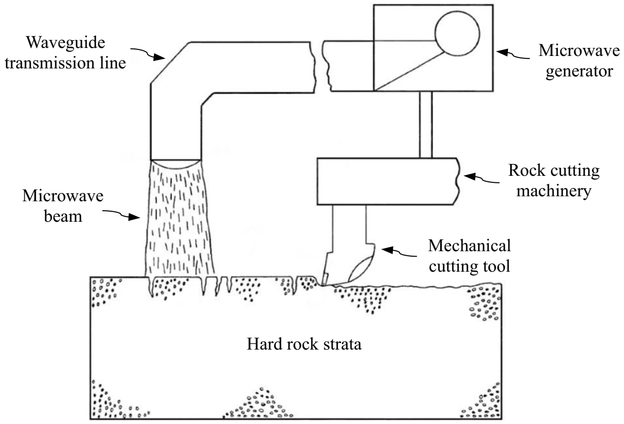


Fig. 1 Schematic diagram of microwave-assisted mechanical rock cutting (Lindroth et al. 1991)

energy-saving, and having no secondary pollution (no dust or noise), the technology of microwave-induced fracturing of hard rock has been considered as a potential method for rock fracturing and breaking (Lu et al. 2017, 2019; Lu 2018). Realising microwave-assisted mechanical rock cutting (Fig. 1) using the microwave-induced hard rock fracturing technique can prolong the mechanical life and improve the efficiency of rock breaking operations (Lindroth et al. 1991; Hassani and Nekoovaght 2011; Hassani et al. 2016; Lu et al. 2016). Shield machines and tunnel boring machines (TBMs) have been increasingly used in tunnelling engineering, where, due to the presence of boulders, the shield machine is subjected to a series of problems such as severe cutter wear, deformation of the tool apron, and difficulty in cutter change-out (Nishitake 1989; Filbà et al. 2016; Li and Yuan 2018). During the tunnelling of hard rocks by TBMs, the disc cutter is worn and frequently changed-out, thus increasing the cost of maintenance and influencing construction progress (Entacher et al. 2014; Jain et al. 2014; Xia et al. 2015; Rostami 2016). The design of cutter heads of shield machines and TBMs is closely related to the properties of rocks and prevailing geological conditions (Deliormanlı 2012; Xia et al. 2012, 2018; Cheng et al. 2018). The mechanical strengths (uniaxial compressive strength, tensile strength, and point load strength, etc.) of rocks are important parameters influencing the service life and penetration of disc cutters on TBMs (Wijk 1992; Boniface 2000; Ramezanzadeh et al. 2004). Microwave treatment can significantly decrease the strength of rocks (Peinsitt et al. 2010; Hassani et al. 2016; Lu et al. 2016; Li et al. 2017; Lu 2018), and, thus, can improve the service life and penetration of disc cutters. Therefore, by introducing microwave heating technology into shield machines or TBMs, the boulders or hard rocks can be pre-fractured through microwave treatment. In this way, cutter wear can be reduced to improve tunnelling efficiency.

The microwave-induced hard rock fracturing technique can be used to cause stress release from rock masses in deep underground engineering works to reduce the risk of geological disasters caused by high-stress concentrations. Increasing use of tunnels for water conservancy and hydropower projects, and transportation tunnels and mining developing into deeper rock, however, a rockburst can occur when tunnelling through rock masses in deep underground engineering works owing to the rock masses releasing compression-induced potential energy under the effects of high stress (Feng et al. 2015a, 2016). Rockbursts frequently appear at working faces, when energy is accumulated in the surrounding rocks (Li et al. 2012; Feng et al. 2015b). Stress-release technology can effectively mitigate against geological disasters induced by high-stress concentrations, so it is widely applied in underground mining and sometimes underground engineering in non-uniform geomechanical conditions (including large depth and high-stress conditions) (Mazaira and Konicek 2015). Fracturing the surface of rock masses through microwave treatment can release some of the energy, thus decreasing rockburst risk at the working face. In addition, when conducting microwave-induced fracturing of hard rock, the rock masses can be pre-fractured while also setting boreholes for stress release. In this way, a fracture zone can be formed in the interior of the surrounding rocks to reduce stress and energy concentration. The schematic diagram of stress released from rock masses in deep underground engineering using microwave-induced hard rock fracturing technology is shown in Fig. 2.

In 1945, a radar engineer in the United States accidentally verified the heating effect of microwaves and Raytheon produced the first microwave oven in 1947. Until the 1940s, microwave heating evolved to commercial industrial use and it did not become a household product until the 1960s (Osepchuk 1984). At present, microwave technology has

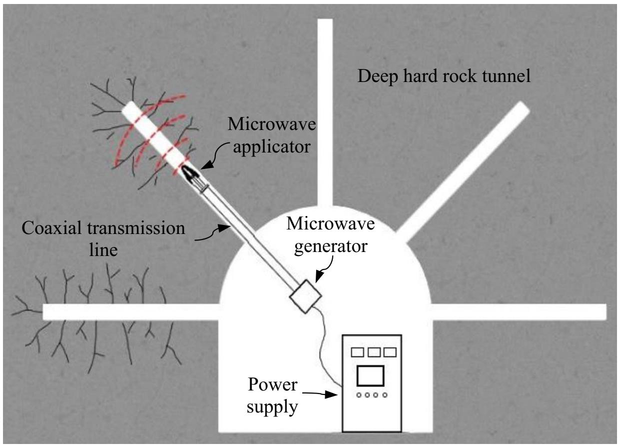


Fig. 2 Stress release from rock masses by microwave-induced hard rock fracturing technology

matured and is widely applied in food heating and drying. The microwave apparatus used for heating and drying materials generally appears as cavity type and tunnel type, and the microwaves are output at a high power generally based on some multi-magnetron combination.

In mineral processing, and metallurgy research, the University of Nottingham, UK, carried out numerous related research projects on microwave-assisted mineral processing including mineral separation, grinding, purification, and the reaction mechanisms of microwaves on rocks (Kingman et al. 1998, 2000, 2004a, b; Kingman and Rowson 1998; Vorster et al. 2001; Batchelor et al. 2016; Buttress et al. 2016; Ferrari-john et al. 2016; Monti et al. 2016). Moreover, ore grinding and comminution tests were conducted on varieties of ores before, and after, microwave treatment (Kingman et al. 2000, 2004a, b). Based on the Bond work index, the grindability of ores was investigated (Kingman et al. 1998, 2000). Through testing, it can be seen that microwave treatment can significantly reduce the Bond work index of ores, which implied that microwave treatment can decrease the energy required for fragmentation of ores (Kingman and Rowson 1998; Vorster et al. 2001; Jones et al. 2002; Whittles et al. 2003). The microwave treatment was conducted in the device with single-mode or multimode cavities at a frequency of 915 or 2450 MHz owing to it being applied to small-sized ore samples.

In geotechnical engineering and mining engineering, Hartlieb and Grafe (2017), and Hartlieb et al. (2012, 2016, 2018) investigated the thermo-physical properties and the crack and failure mechanism of varieties of rocks using an industrial microwave oven with a multimode cavity and an open-ended waveguide set-up. By using a microwave oven with a multimode cavity working at a power of 3 kW and a frequency of 2450 MHz, Peinsitt et al. (2010) investigated the influence of microwaves on uniaxial compressive strengths, wave velocities, and heating characteristics of basalt, granite, and sandstone in dry and water-saturated states. Using a microwave device with a multimode cavity, Hassani and Nekoovaght (2012), Hassani et al. (2007, 2008, 2011, 2016), Satish et al. (2006), Nekoovaght and Hassani (2014), and Nekoovaght et al. (2014a) investigated the uniaxial compressive strengths and tensile strengths of varieties of rocks under different microwave power levels. They explored the influence of distance from microwave source on the surface temperatures of hard rocks by comparing results obtained through experiments and numerical simulations. Moreover, they also discussed the beneficial effect of microwave-assisted rock breakage technology on future mining in space (Satish et al. 2006; Nekoovaght et al. 2014b). Lu et al. (2017) and Tian et al. (2019) investigated the microwave absorption capacity of common rock-forming minerals using an industrial device with a multimode cavity operating at a power of 6 kW and a frequency of 2450 MHz and classified the main rock-forming minerals therewith. Zheng et al. (2017) explored the influences of power and irradiation time of microwave treatment on the surface temperature and wave velocity of Austral black gabbro by employing a single-mode applicator with a power of 2 kW and a frequency of 2450 MHz.

The aforementioned items of equipment are mainly made of single-mode or multimode cavities, and microwaves can be reflected and absorbed by rocks in closed cavities (Fig. 3). In this case, rock samples do not suffer from applied external load. The type of microwave apparatus can be used in laboratory experiment to investigate the effect of microwave treatment on thermo-physical and mechanical properties of unloaded rocks: however, field-scale rock samples cannot be placed in the cavity-type microwave apparatus. For the real application of microwave-induced hard rock fracturing technology in underground engineering, it is necessary to develop a novel (open-type) microwave-induced fracturing apparatus (OMWFA). In addition, field rock masses are subjected to geostresses, so that the fracturing effects of microwave treatment on same rocks are different under different stresses. Therefore, it is necessary to analyse the fracturing effect of microwave treatment on rocks under the effect of applied load. Therefore, aiming at the microwave-assisted mechanical rock breakage and the stress release of rock masses of deep underground engineering, an OMWFA was developed. Two microwave-based fracturing modes (subsurface and borehole) of hard rock were realised. The laboratory experiment was carried out using the apparatus to investigate the fracturing effects of the two microwave-based fracturing modes on basalt samples. Moreover, by combining the OMWFA with a press machine for testing rocks, the influence of unidirectional stress on the fracturing effect of microwave treatment on rock surfaces was investigated.

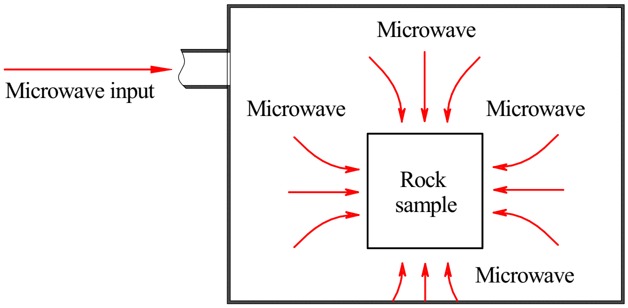


Fig. 3 Schematic diagram of radiation of a cavity-type (stationary field) microwave applicator

2 Experimental Equipment and Method

2.1 A Novel Microwave System

The OMWFA is made of a microwave power supply, a magnetron, an isolator, a coupler, an impedance tuner, a waveguide transmission line, and a microwave applicator (Fig. 4). The microwave power supply is used to convert alternating-current (AC) into direct-current (DC) to thus create conditions for operation of the magnetron. The magnetron aims to transfer DC electrical energy into microwave energy to provide stable microwave power in the form of continuous waves. The isolator is employed to transmit unidirectional, circulatory microwave energy and the water cycle is applied to absorb the microwave energy reflected from the microwave applicator so as to protect the magnetron. The impedance tuner is used for impedance matching. The microwave applicator aims to transmit microwave energy produced by the microwave generator to rock media, so as to heat, and fracture, the rocks. A continuous microwave source working at a frequency of 2.45 GHz and at variable power of up to 15 kW is applied. Compared with the microwave apparatus operating at a frequency of 915 MHz, the microwave-based fracturing apparatus confers the advantages of a small volume, so it can be combined with other mechanical rock breaking devices.

The transmission mode of microwave energy is changed from rectangular waveguide transmission to coaxial transmission using the coaxial converter. The coaxial converter is connected to the applicator by a coaxial transmission line to allow long-distance, low-loss transmission of microwave energy. As the coaxial transmission line and the coaxial applicator both are cylindrical and of small cross-sectional dimensions, the equipment can be used to fracture boreholes in rock masses by application of microwave treatment. Through the mode of coaxial transmission, the fracturing system through microwave treatment is combined with the rock loading system to achieve the coupled mechanical–thermal loading of the rock masses through microwaves. On this basis, the influence of unidirectional stress on microwave-induced surface fracturing of hard rocks is investigated. During testing, a metal net is used as shielding to avoid microwave interference with signal transmission to/from the press machine.

2.2 Microwave Applicator

Different heating functions can be realised using different microwave applicators. To fracture large-size rocks or engineering rock masses through microwave treatment, a flat-nose type applicator (able to focus microwave energy) (Fig. 5) for subsurface fracturing of hard rocks through microwave treatment and a coaxial-type applicator (Fig. 6) for fracturing borehole in hard rocks through microwave

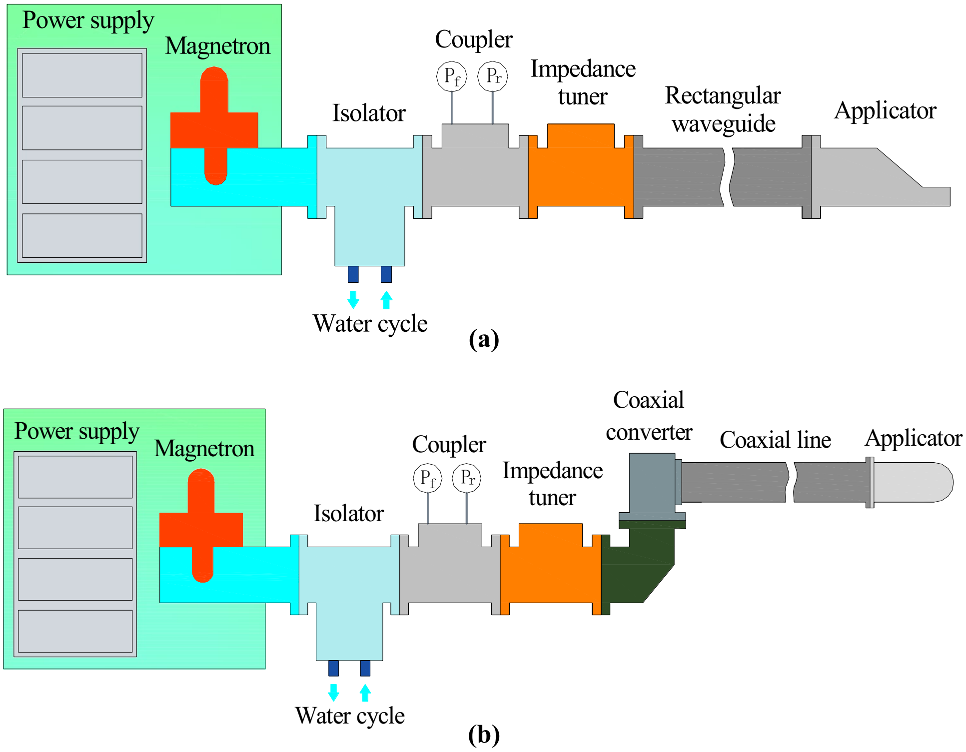


Fig. 4 Schematics of the system used for fracturing hard rocks: **a** the system for subsurface fracturing of hard rocks and **b** the system for borehole fracturing in hard rocks

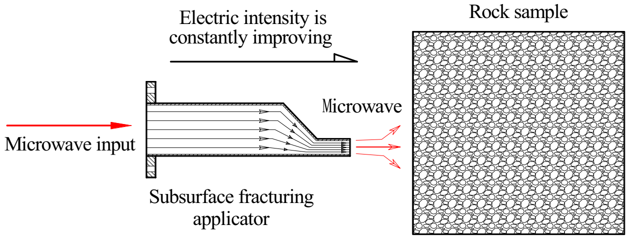


Fig. 5 Schematic diagram of the flat-nose-type (able to focus microwave energy) applicator for subsurface fracturing of hard rock

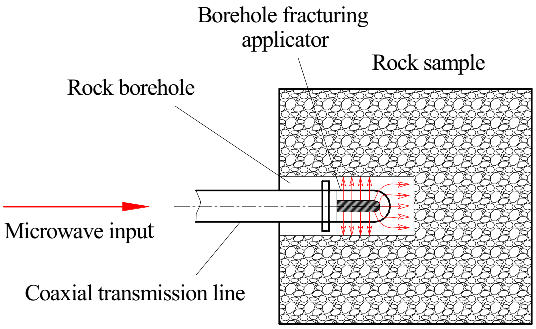


Fig. 6 Schematic diagram of the coaxial-type applicator for fracturing boreholes in hard rock

treatment were developed. The subsurface fracturing applicator can be used to fracture surfaces of rocks through microwave treatment, while the flat-nose type of microwave applicator can focus microwave energy, and is designed based on the following mechanism: the waveguide transmission line of microwaves can be applied in single-mode transmission (TE_{10} mode) and its transmission parameters are only related to the broadband rectangular waveguide while having no relationship with the narrowband waveguide. On the condition that the electric field intensity does not cause ionisation, the narrow side of the rectangular waveguide can be compressed. In this way, the microwave power can be focused to increase the electric field intensity in the diametric plane of the emission port of the microwave applicator, thus focusing the emitted microwave energy. Furthermore, the power density of the radiant surfaces can be significantly improved when microwaves irradiate rock surfaces, leading the rocks to become rapidly heated and fractured. The radiation mechanism of the subsurface fracturing applicator is shown in Fig. 5.

The coaxial applicator (Fig. 6) for fracturing boreholes in hard rock through microwave treatment can be connected with a coaxial transmission line to realise the long-distance transmission of microwave energy. In this way, rock at greater depth down a borehole can be fractured through microwave treatment. The applicator is mainly composed of an internal conductor, an external conductor, and filling media. The internal and external conductors are installed coaxially and both are made from high-conductivity metal materials. The space between the internal and external conductors is filled with high-temperature resistant, low-loss, wave-transparent materials as filling media so as to avoid air ionisation and breakdown under microwave radiation. The external conductor is generally made in a stepped shape to reduce the thermal transfer from the borehole at high temperatures to the applicator (thus avoiding damage to the applicator).

To achieve the subsurface fracturing and borehole fracturing of different sized rock samples, two flat-nose-type applicators and two coaxial applicators were designed. Meanwhile, the two standard rectangular waveguides of WR430 (109.2 mm × 54.6 mm) and WR340 (86.4 mm × 43.2 mm) and the coaxial waveguides were used in the microwave system. The dimensions of the applicators and waveguides, and parameters related to the test method, are summarised in Table 1.

2.3 Experimental Samples and Methods

The basalt was taken from Chifeng in Inner Mongolia, China, and was shaped into cuboidal samples of different dimensions. The samples were intact, and without visible

Table 1 Applicator specification and corresponding test methods

Applicator	Transmission waveguide	Dimensions or diameter of applicator (mm)	Distance to the rock (mm)	Dimensions of sample (length or $l \times w \times h$; mm)	Diameter of borehole (mm)	Microwave power (kW)	Irradiation time (min)
Flat-nose applicator	WR430 and WR340	86.4 × 20.0 (radiation port)	10	100/200	–	3/15	1, 2, 3
	WR430	109.2 × 20.0 (radiation port)	10	400 × 400 × 250	–	6	3, 5
Coaxial applicator	WR430 and coaxial line	40	Centre of the hole	200	50	3	5, 10, 15
	WR430 and coaxial line	75	Centre of the hole	400 × 400 × 250	90	6	10, 15

cracks. The samples were used to conduct surface fracturing, borehole fracturing, and unidirectional loading tests. A circular borehole was drilled on one end surface of the sample for borehole fracturing test purposes. The borehole had a diameter chosen on the basis of the sample size and its depth was about the half of the length of one side of each sample. The samples were subjected to microwave-induced fracturing tests under a power of up to 15 kW and different irradiation times. The details of the test method and dimensions of the samples are summarised in Table 1.

The two end surfaces normal to the loading direction of the sample used for unidirectional static loading were ground and the evenness of the end surfaces satisfied the requirement of laboratory loading tests. A cubic sample with a side length of 100 mm was used in tests of microwave-induced fracturing under a unidirectional stress state in which the unidirectional static stresses were separately set to 0, 10, and 30 MPa. The average uniaxial compressive strength of the basalt samples was 283 MPa and the density was 2.9 g/cm^3, so the applied 30 MPa unidirectional stress will simulate approximately 1000 m of in situ overburden pressure. The designed stress was applied at a rate of 0.5 MPa/s, and then, the samples were subjected to microwave treatment at a microwave power of 3 kW for an irradiation time of 3 min. Under unidirectional static stress, the schematic diagram of fracturing the samples through microwave treatment is illustrated in Fig. 7.

3 Test Results

3.1 Effects of Microwave-Induced Subsurface Fracturing

The fracturing effects of microwave treatment on subsurfaces of basalt samples with different dimensions after different irradiation times are shown in Fig. 8. Cracks with a length equal to the size of the 100 mm cubic samples formed under irradiation at 3 kW were mainly found in surfaces irradiated by microwaves and the primary cracks radiated along diagonal lines, that is, extended from the approximate centre of the samples to their periphery (Fig. 8a). It was because more microwave energy accumulated on the surface of the samples directly facing the radiation port that cracks extended from the centre under the effect of thermal stress generated therefrom. The longer the irradiation time, the more severe the cracking and the longer the cracks on all four side surfaces: when samples were irradiated for 1 min, cracks hardly occurred on the four side surfaces, and after an irradiation time of 2 min and 3 min, the cracks on the side surfaces almost extended to the bottom surface. After being irradiated for 1 min, the surface of the sample normal to the radiation port suffered clumpy exfoliation, probably because minerals sensitive to microwaves had accumulated at that position, such that high local stress concentrations appeared thereat.

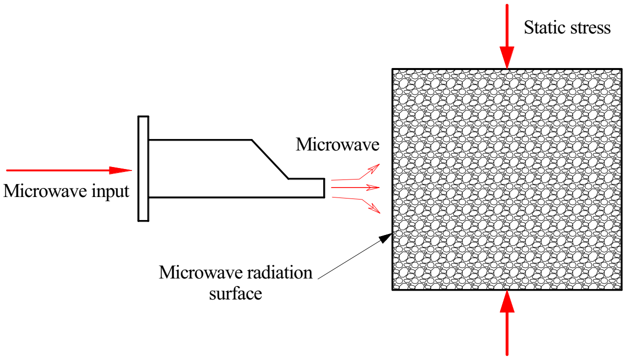


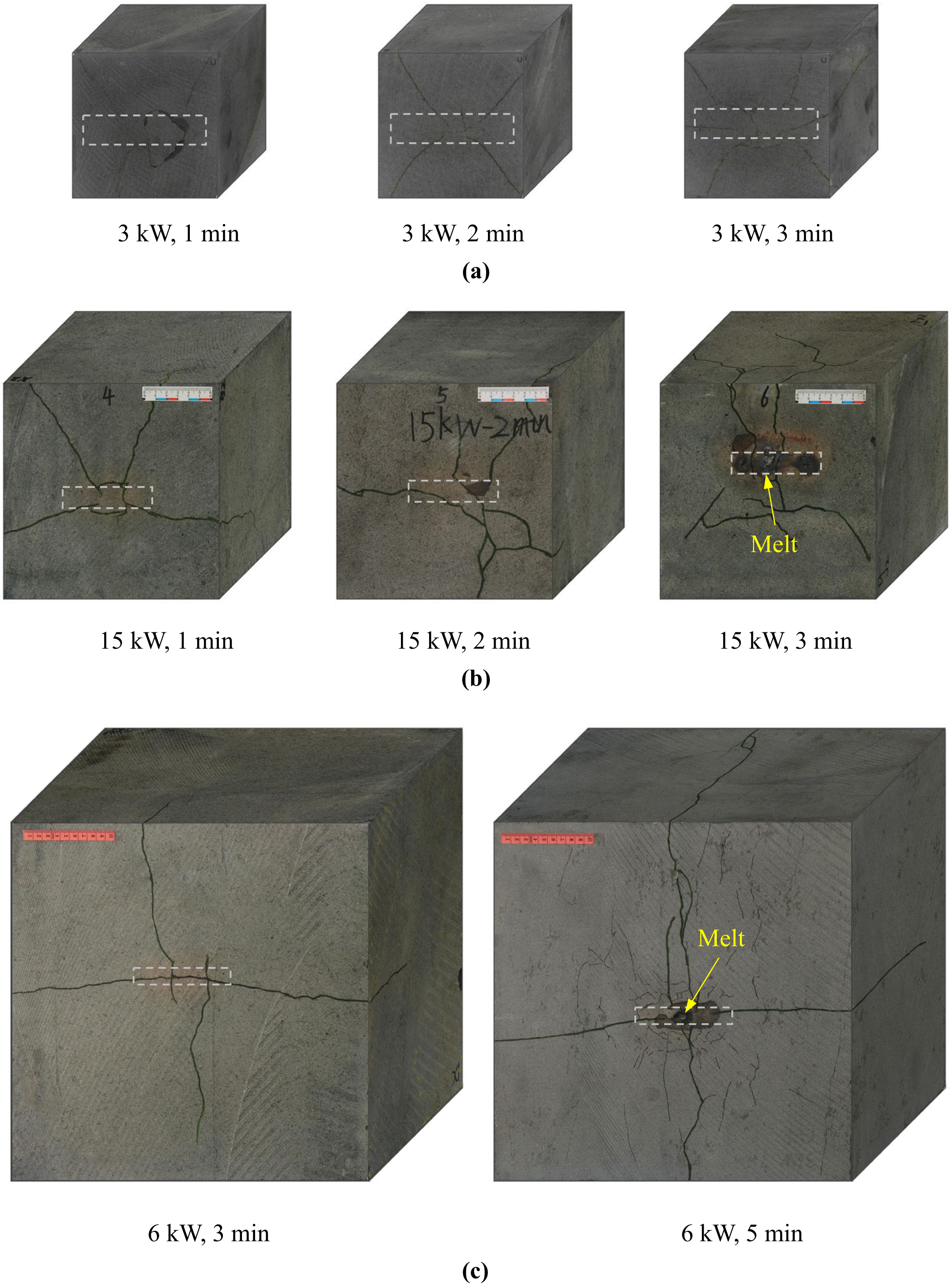
Fig. 7 The schematic of sample fracturing by microwave treatment under unidirectional static stress

The fracturing effect of the irradiated surface of the cubic sample with the side length of 200 mm at 15 kW was such that it contained four distinct cracks after an irradiation time of 1 min, small pieces exfoliated after an irradiation time of 2 min, and it melted after irradiation for 3 min (Fig. 8b). The fracturing effect of the 400 mm × 400 mm × 250 mm rectangular samples under irradiation at 6 kW was such that it generated three distinct cracks on the irradiated surface after an irradiation time of 3 min, and underwent a significant crack extension whereby cracks extended to the bottom surface within an irradiation time of 5 min (Fig. 8c). This differed from the other two dimensions, in which cruciform primary cracks were generated.

3.2 Effects of Microwave-Induced Borehole Fracturing

The fracturing effect of microwave treatment and the expanded view of one of the 400 mm × 400 mm × 250 mm cuboidal samples are shown in Fig. 9: the longer the irradiation time, the more severe the cracking and the longer the cracks on the irradiated surface and all four side surfaces. On the end surface of these samples on which there was a borehole, the cracks radiated from the borehole and the primary cracks extended along the direction passing through the centre of the borehole. The primary cracks penetrated to the four side surfaces perpendicular to the end surface where the borehole was drilled along the side boundaries of the samples. The primary cracks on the side surfaces, and branching cracks from the primary cracks, extended to the bottom surface of the samples.

As a result, borehole fracturing had a significant fracturing effect in such cases. At 3 kW and 6 kW applied microwave power, after the sample was irradiated for 10 min or 15 min, the cracks almost penetrated the entire sample.



3 kW, 1 min 3 kW, 2 min 3 kW, 3 min

(a)

15 kW, 1 min 15 kW, 2 min 15 kW, 3 min

(b)

6 kW, 3 min 6 kW, 5 min

(c)

Fig. 8 Extension of cracks on fractured surfaces of **a** 100 mm cubic samples, **b** 200 mm cubic samples, and **c** 400 mm × 400 mm × 250 mm cuboidal samples after different irradiation times: cracks on the microwave irradiated surface propagated outwards from the approximate centre of the sample; with increasing irradiation time, the cracks gradually extended to four side surfaces vertical to the radiant surface (grey rectangular dashed boxes show the location of microwave radiation port)

Therefore, microwaves with a power of up to 6 kW had a favourable borehole fracturing effect on 200-mm cubic basalt samples and 400 mm × 400 mm × 250 mm rectangular samples. The fracturing of boreholes within hard rocks using microwave treatment can be used to pre-fracture rock masses encountered in deep underground engineering works, and a fracture zone can be formed within the surrounding rocks to reduce the stress and energy concentration therein.

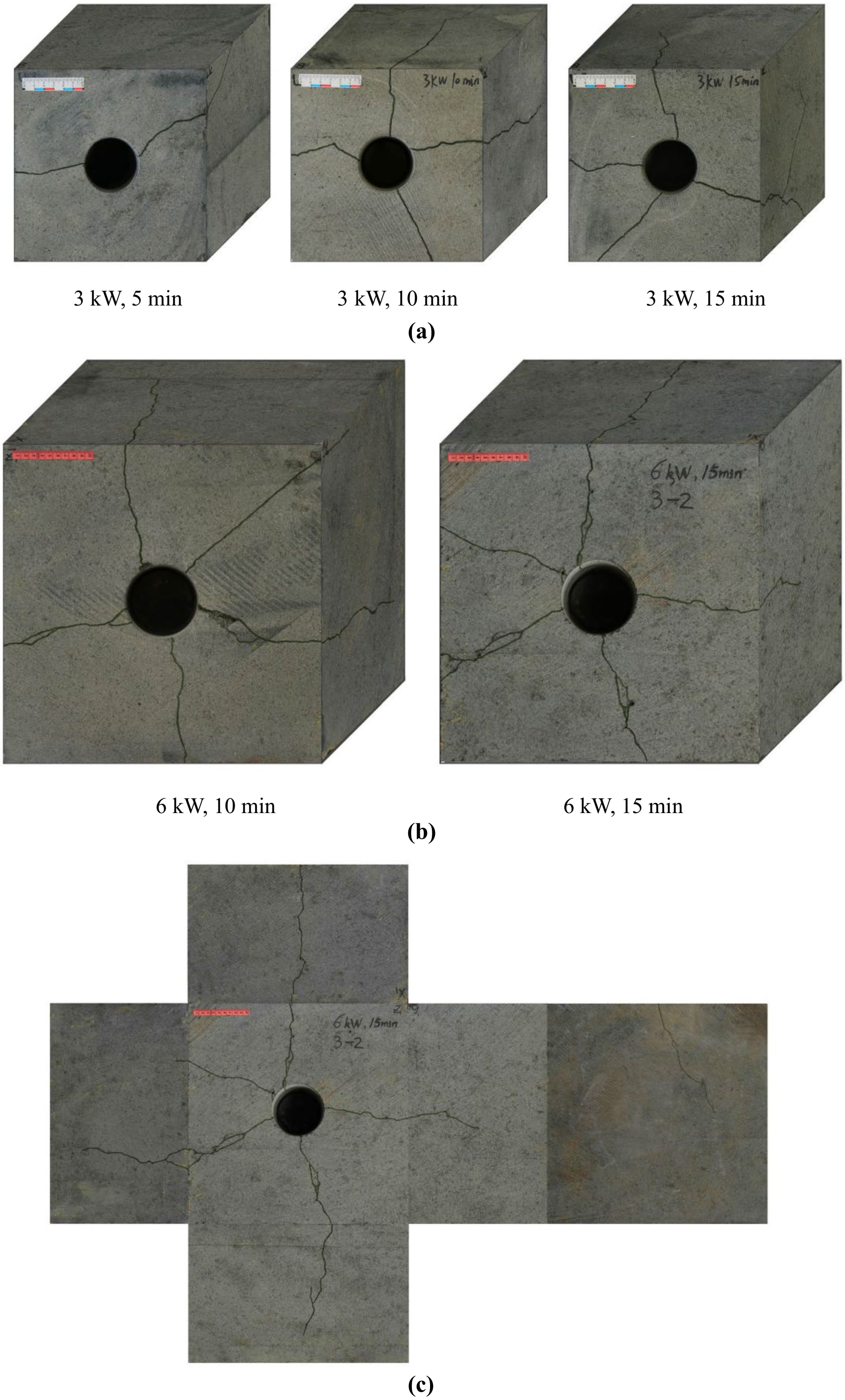


Fig. 9 The effect of microwave-induced fracturing around boreholes in hard rock. **a** Side length of 200 mm cubic samples, **b** 400 mm × 400 mm × 250 mm cuboidal samples and **c** expanded view of the 400 mm × 400 mm × 250 mm rectangular sample after an irradiation time of 15 min. The cracks radiated outward from the borehole; primary cracks extended along directions passing through the centre of the borehole; primary cracks penetrated to the four side surfaces vertical to the end surface of the borehole along the side boundaries of the sample

3.3 Fracturing Effect Under Unidirectional Stress

The rock masses encountered in engineering operations are all under different stress states. The fracturing effect on rocks under stress is different from that on rocks under self-weight alone. To provide guidance for engineering application, investigating the fracturing mechanism and fracturing effect on rocks under different stress states is important. The fracturing effects of microwave treatment on surfaces of 100-mm cubic samples under different stress states are displayed in Fig. 10.

Under no load, the cracks mainly appeared on the irradiated surface and the cracks approximately radiated outward along diagonal lines or formed the cruciform cracks (Fig. 8). By contrast, under unidirectional stress, the cracks were mainly found on the irradiated surface and the two end surfaces perpendicular to the loading direction. The surface irradiated by microwaves exhibited exfoliation of laminar rocks, which occurred near the centre of the radiant surface, namely, the location directly facing the microwave port. When the unidirectional stress was 10 MPa, there were small areas of exfoliated rocks; while the sample surface irradiated by microwaves, when under an applied stress of 30 MPa, showed a large area of exfoliation. The cracks on

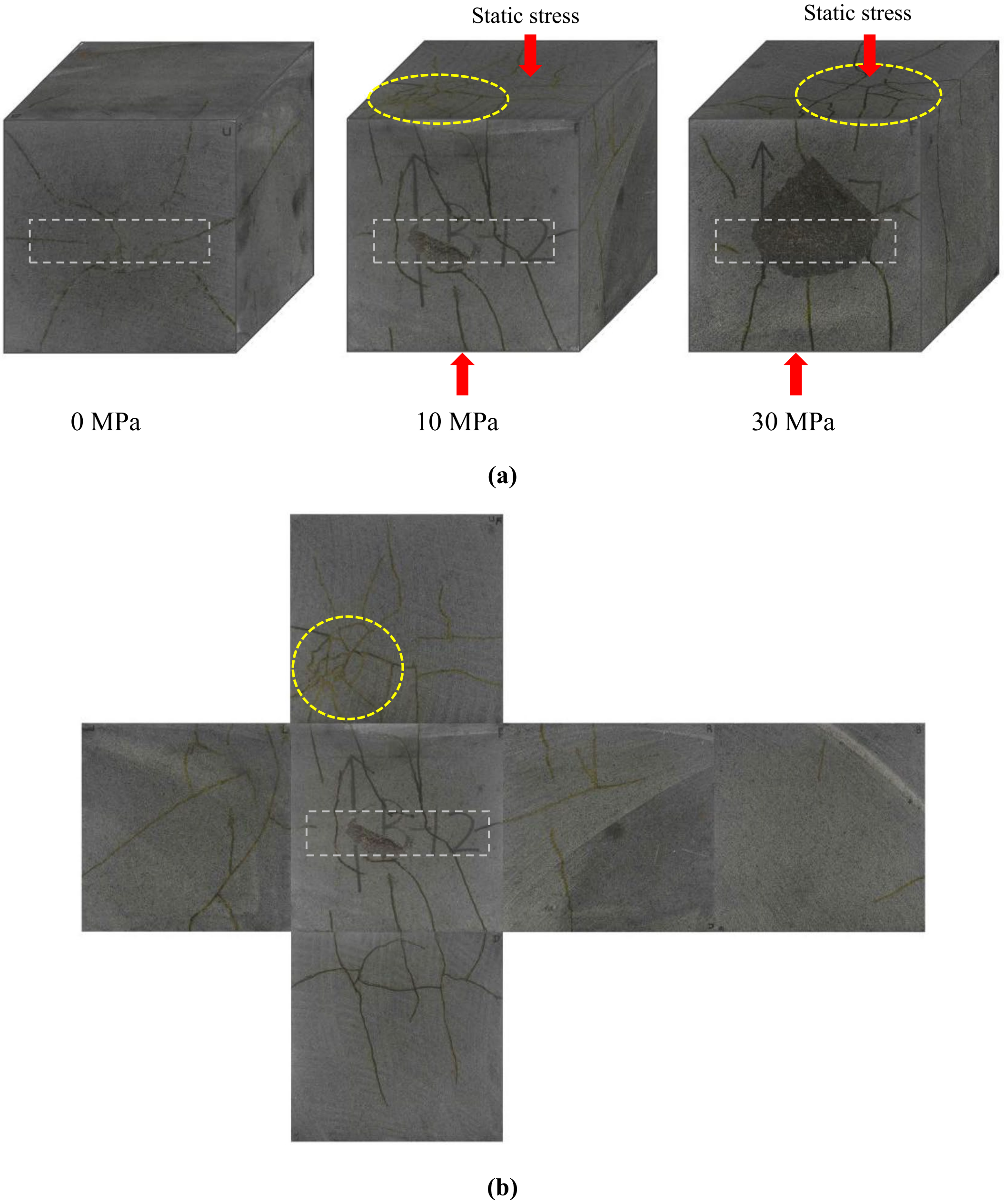


Fig. 10 The effect of subsurface fracturing under the condition of unidirectional static loading, with unidirectional stress of **a** 0, 10, and 30 MPa, and **b** is an expanded view of the sample subjected to a static stress of 10 MPa: cracks were mainly concentrated on the irradiated surface and the two end surfaces perpendicular to the loading direction; the approximate centre of the irradiated surface underwent exfoliation; the higher the stress, the larger the area of exfoliation; the two end surfaces perpendicular to the loading direction contained a large crack-extension zone and local stress concentration resulted in the generation of network-shaped cracks

the two end surfaces perpendicular to the loading direction extended to form a network and the extension of network-shaped cracks did not appear at the centre of the sample surface but occurred randomly. This implied that local stress concentration occurred during microwave treatment. Primary shear cracks appeared on the four surfaces parallel to the loading direction, which was induced by the effect of unidirectional stress. The results indicated that unidirectional stress promoted the extension of cracks in the sample.

Overall, the unidirectional stress state promoted the fracturing effect of microwave treatment on the surfaces of hard rocks, while the biaxial stress conditions maybe restrain the fracturing effect of microwave treatment on hard rocks. The effects of high-power (100 kW) microwave-induced fracturing on the effects of the two modes (the subsurface fracturing and the borehole fracturing) of large-sized rock samples under biaxial and true triaxial stress conditions will be explored in future research.

3.4 Reduction in P-Wave Velocity

P-wave velocity tests were carried out on the samples before and after being subjected to microwave treatment. During testing, the probe of an acoustic logging tool was aligned with the centre of the sample surface and the test results of surface fracturing mode trials are displayed in Fig. 11. At an applied microwave power of 3 kW, the P-wave velocities of the cubic samples with the side lengths of 100 mm both decreased to different extents and the longer the irradiation time, the greater the decrease in P-wave velocity. The reduction in P-wave velocity indicated that the internal structure of the samples changed after microwave treatment. On the whole, it can be seen that the decrease in P-wave velocity in the direction of radiation exceeded that along the side surfaces by comparing Fig. 11a, b. For example, the P-wave velocities of the 100-mm cubic samples separately decreased by 7.3%, 12.9%, and 22.2% (in the three irradiation times assessed) along the direction of microwave treatment while separately decreased by 2.1%, 3.7%, and 5.9% (in the three irradiation times assessed) along the side surfaces. The reason for this was that, after microwave treatment, multiple cracks close to the radiation source will decrease the P-wave velocity, but side cracks could also exert a significant influence thereon. The damage of the surface irradiated by microwaves was higher than that on the other four side surfaces, which conformed to the conclusion drawn about the fracturing effects of microwave treatment on such samples. The work of Hartlieb et al. (2012) and Hassani et al. (2016) also proved that microwave treatment can damage rocks.

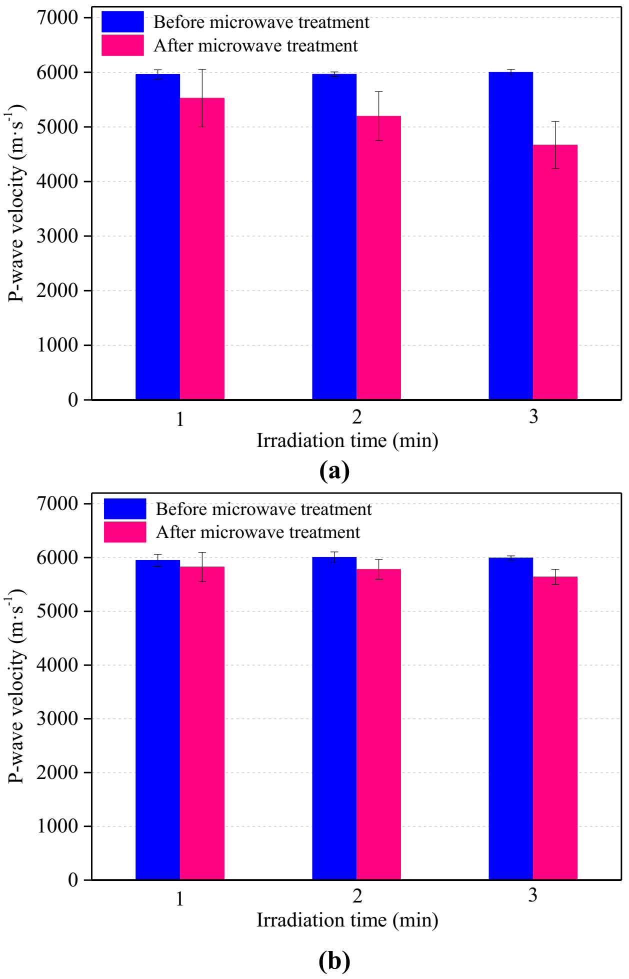


Fig. 11 The influence of surface fracturing mode on P-wave velocity at an applied microwave power of 3 kW (100-mm cubic samples): **a** P-wave velocity along the microwave radiation axis and **b** along one of the side surfaces (the tests were repeated in triplicate and the data are presented as means (± standard deviation))

The P-wave velocity, in borehole fracturing mode, at a power of 3 kW (in a cubic sample with a side length of 20 cm) also decreased and the longer the irradiation time, the greater the decrease in P-wave velocity (Fig. 12). The P-wave velocity in the directions perpendicular to the borehole separately decreased by 2.2%, 6.0%, and 8.4% and separately decreased by 1.9%, 5.9%, and 8.7%. This indicates that the damage caused by borehole fracturing mode in the surrounding rock was consistent.

The influence of surface fracturing mode on the P-wave velocity of 100-mm cubic samples under unidirectional static loading (at a microwave power of 3 kW) is as seen in Fig. 13. The P-wave velocity in all three directions decreased with increasing unidirectional stress. It is noteworthy that the reduction in P-wave velocity along the microwave radiation (separately decreasing by 21.2%, 23.3%, and 25.0%) exceeded that in the third direction (separately decreasing by 5.9%, 7.7%, and 12.9%) which exceeded that in the loading direction (separately decreasing by 4.2%, 6.3%, and 9.1%). This is because the loading direction was restrained by unidirectional stress. After microwave treatment, there

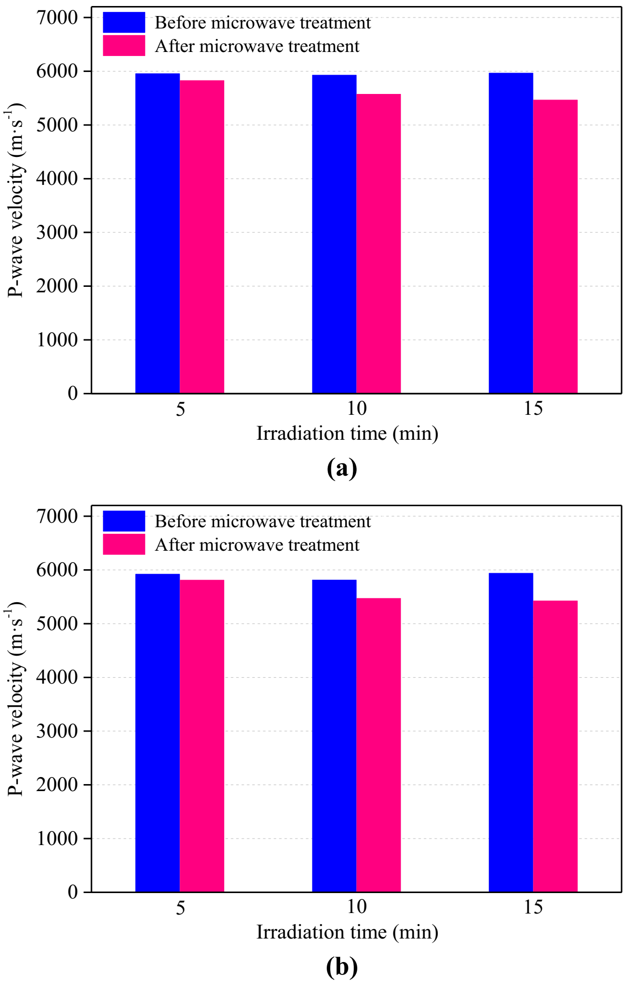


Fig. 12 The influence of borehole fracturing mode on P-wave velocity at an applied microwave power of 3 kW (cubic sample, side length, 20 cm): **a** P-wave velocity perpendicular to the borehole and **b** the other direction perpendicular to the borehole

were fewer micro-cracks formed along the loading direction in these basalt samples, while more were generated in the direction of microwave radiation. In the third direction, moderate micro-crack propagation occurred.

3.5 Field Testing

A field trial of microwave-induced borehole fracturing was carried out at the 5-2 drainage gallery of the underground powerhouse on the right bank of Baihetan Hydropower Station. The rocks surrounding the area of interest are mainly composed of cryptocrystalline basalt, plagioclase-phyric basalt, amygdaloidal basalt, and breccias in the $P_2\beta_3^5$–$P_2\beta_5^1$ layers, and the experimental site is mainly composed of cryptocrystalline basalt (Jiang et al. 2017). The horizontal and vertical burial depths of the main and auxiliary powerhouses at the right bank, with a length of 434 m, are

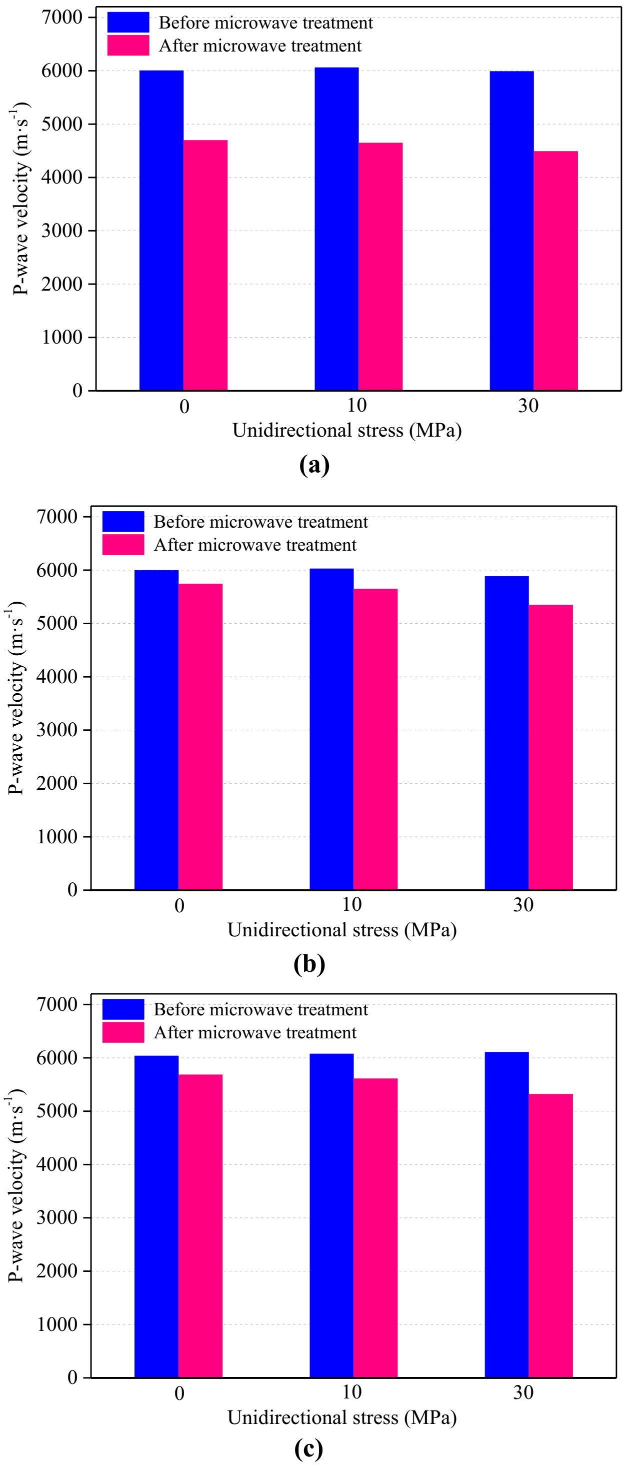


Fig. 13 The influence of surface fracturing mode on P-wave velocity of 100-mm cubic samples under unidirectional static loading (at an applied microwave power of 3 kW): **a** P-wave velocity along the microwave radiation axis, **b** the loading direction, and **c** the third direction

420–800 m and 420–540 m, respectively. For the geostresses on the right bank, the minimum principal stress is approximately 13.0–16.0 MPa and the maximum principal stress is between 22.0 and 26.0 MPa with an orientation of N0°–20°E and a dip angle of 2°–11° (Duan et al. 2017). Coupled boreholes were drilled in the rock masses at the test point, to a depth of about 2 m, at a borehole diameter of 90 mm, and a distance between the boreholes of 0.5 m. The applied microwave power was 10 kW and the irradiation time was 3 min. Before, and after, microwave treatment, digital borehole televiewer and acoustic wave tests (around the borehole and between the boreholes) were separately carried out.

The results obtained by digital borehole televiewer and acoustic wave testing are displayed in Figs. 14 and 15. The borehole was irradiated using microwaves at an output power of 10 kW over three rounds of treatment. The irradiation spacing and time were the same as those used in the borehole. After microwave treatment, obvious fractures (measuring 3–7 cm) were seen in zones irradiated by microwaves during the three rounds of testing. This revealed that a microwave power output of 10 kW can exhibit a favourable fracturing effect on boreholes in rocks. The average sound velocity around the borehole in the zones irradiated by microwaves significantly decreased (by about 27%), which was caused by the wall of the borehole and the interior of the rock mass being damaged. Compared with the sound velocity around the borehole, the sound velocity between the boreholes underwent a lower decrease in those zones irradiated by microwaves.

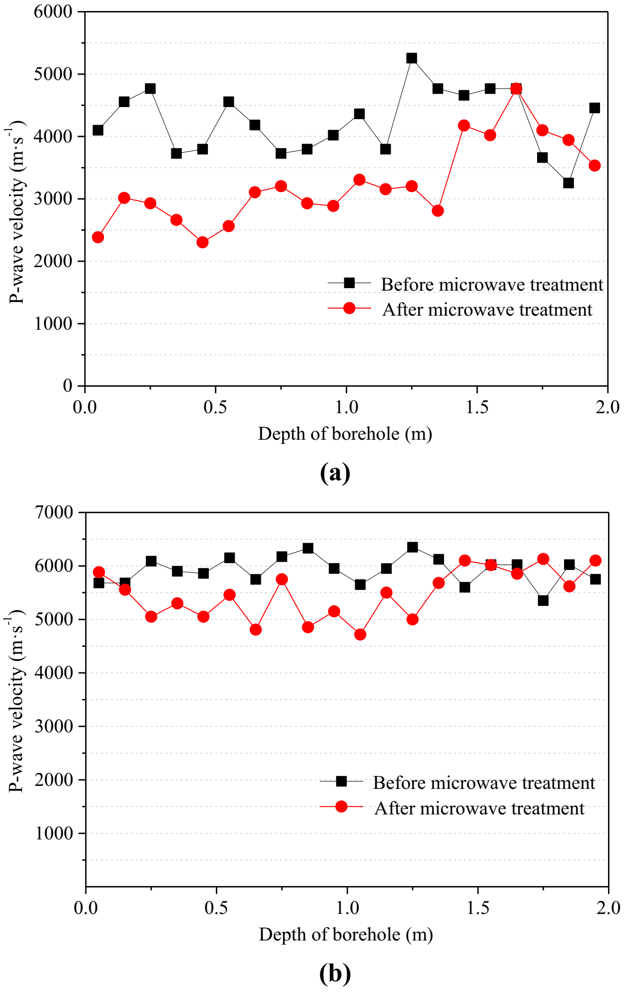


Fig. 15 Measured sound velocities **a** around the borehole and **b** between boreholes before, and after, microwave treatment

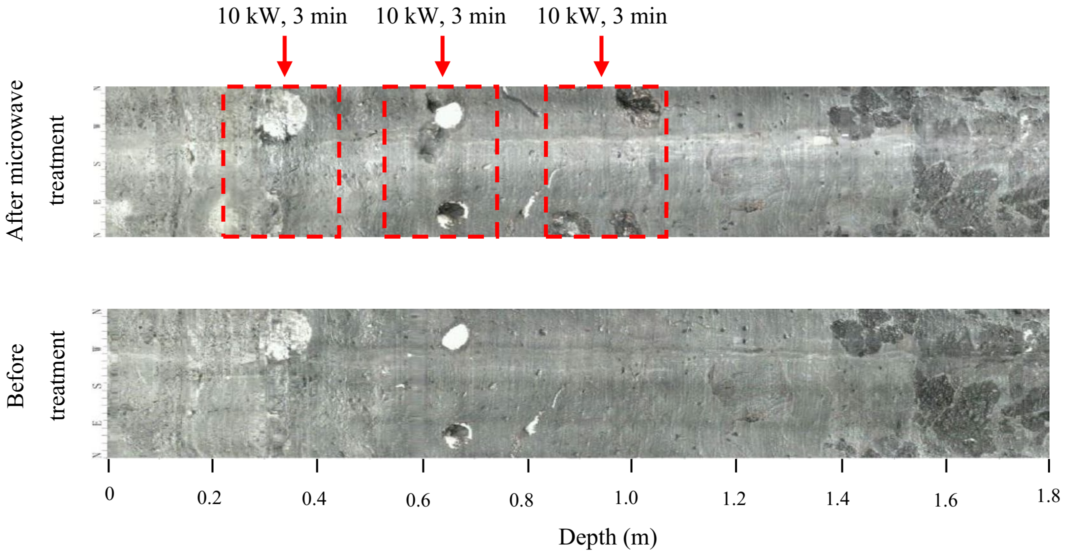


Fig. 14 Digital borehole televiewer results before, and after, microwave treatment

4 Discussion

4.1 Microwave-Assisted Mechanical Rock Breakage

Wijk (1992) presented a mathematical model which proposed an equation for TBM cutter wear by considering rock strength parameters and the Cerchar abrasivity index (CAI). In the equation, uniaxial compressive strength and point load index of the rock are involved, and the cutter life is inversely proportional to $(\sigma_c\sigma_{PTL})^{1/2}$ and CAI^2. CAI is the most widely known test method for identification of rock abrasivity and the value is related directly to cutter life and the rate of advance of TBMs in the field (Suana and Peters 1982). Deliormanlı (2012) revealed a relationship between CAI, uniaxial compressive strength, and direct shear strength. The cutter life L and CAI can be calculated from the following (Wijk 1992; Deliormanlı 2012):

$$L = \sum Dw^3 \frac{\cot(\theta)}{F_n\sqrt{\sigma_c\sigma_{PTL}}(\mathrm{CAI})^2}, \tag{1}$$

$$\mathrm{CAI} = a\sigma_c + b, \tag{2}$$

$$\mathrm{CAI} = c\sigma_\tau + d, \tag{3}$$

where L is the disc cutter rolling length; D denotes the cutter diameter; w is the width of the cutter edge; θ is one-half of the wedge-shaped disc cutter edge angle; F_n is the normal force applied by the disc cutter; σ_c is the uniaxial compressive strength; σ_{PTL} represents the point load index of the rock; σ_τ is the direct shear strength; CAI is the Cerchar abrasivity index of the rock surface; and a $(a > 0)$, b, c $(c > 0)$, and d are constants.

Penetration rate is an important parameter used to indicate TBM performance. Graham introduced a model in which the penetration rate was calculated using the normal force and uniaxial compressive strength of the rock (Ramezanzadeh et al. 2004). Farmer and Glossop (1980) established a model in which the penetration rate was computed using the average cutter force and the tensile strength. The models include some simplifications and consider neither the rock mass properties nor the cutter properties. The two equations are as follows (Farmer and Glossop 1980; Ramezanzadeh et al. 2004):

$$P = \frac{3490F_n}{\sigma_c}, \tag{4}$$

$$P = \frac{624F_n}{\sigma_t}, \tag{5}$$

where P is the penetration per revolution (mm/rev), and σ_t is the tensile strength. The strength of microwave-treated rocks decreased and there was a linear reduction seen in the rock strength and irradiation time under a certain applied microwave power (Hassani et al. 2016; Lu et al. 2016; Lu 2018). It can be seen from Formulae (1)–(5) that the reduction in rock strength (uniaxial compressive strength σ_c, tensile strength σ_t, direct shear strength σ_τ, and point load strength index σ_{PTL}) can increase the life L and penetration P of the disc cutter of a TBM to some extent.

As seen, the subsurface fracturing effect in 400 mm × 400 mm × 250 mm basalt samples (Fig. 8c), the fracturing range, and depth are applicable to the disc cutter of a TBM. The measured reduction in P-wave velocity (Figs. 11, 13) and the recent literature of Toifl et al. (2017), Zheng et al. (2017), and Hartlieb et al. (2018), both indicate that microwave treatment can induce severe damage in a rock mass. Thus, when a tunnel is excavated in hard rock using a TBM, the microwave-induced subsurface fracturing of hard rocks can be introduced to the disc cutter of the TBM. During the construction process, large network of cracks can be achieved from microwave treatment. If the disc cutter cuts into the crack, it will increase the penetration of the disc cutter, making it easier and faster to cut through the rock. Microwave exposure and disc cutter cutting are carried out simultaneously to increase the rate of advance of a TBM.

4.2 Microwave-Induced Stress Release

Stress release was first used in deep mines in South Africa in the 1950s, as a method for improving the rockburst-prone environment. In the 1980s and 1990s, stress-release technology was one of several measures used for preventing rockbursts in mining areas around the world (Adams et al. 1981; Lightfoot et al. 1996). The mechanism of any stress-release technology is to reduce the occurrence of rockbursts or decrease the intensity of rockbursts by increasing the depth of surface fracture zones in underground caverns. Before excavation, the stress on the rock masses is released, so that the depth of the fractured zone can increase and high-stress zones transfer to greater depth within the solid rock mass. In this case, if the high-stress zone is suddenly damaged, only a finite amount of damage can occur, because the pressure-relief zone on the surface of the rock masses functions as a buffer (Mitri and Saharan 2005; Konicek et al. 2011a, b).

Through using microwave-induced borehole fracturing within hard rocks, the stresses on rock masses in deep underground engineering works can be released. Apart from setting boreholes to release stresses, pre-fracturing the rock masses can form a fracture zone in the interior of the mass of surrounding rocks to reduce the stress and energy concentration therein. Therefore, microwave-induced fracturing of hard rock can be proposed as a means of releasing stresses in rock masses in deep underground engineering works to, thus, mitigate the effects, and prevent, geological disasters induced by high-stress concentrations, for example, avoiding or decreasing rockburst risk. The technology of microwave-induced fracturing of hard rock can hold guiding significance to those exploring and developing new rock breaking and tunnelling methods and to those responsible for construction safety in deep underground engineering works.

5 Conclusions

To realise the engineering application of the microwave-induced hard rock fracturing technology, an OMWFA for fracturing hard rocks through microwave treatment was developed to investigate the subsurface and borehole fracturing effects of microwave treatment on basalt samples. By combining the apparatus and a mechanical press, we explored the influence of unidirectional stress on the fracturing effect of microwave treatment on basalt. Moreover, field tests were carried out on rock masses encountered in underground engineering works at Baihetan Hydropower Station, Sichuan Province, China, by employing OMWFA with a rated power output of 15 kW. Then, the fracturing effects were evaluated using a digital borehole televiewer and conducting acoustic wave testing.

The test results showed that there was a favourable fracturing effect on different dimensions of cuboidal basalt samples using the apparatus developed for fracturing rocks through microwave treatment at series of power levels at a frequency of 2450 MHz. The cracks caused by the microwave-based subsurface fracturing technology radiated outwards from the approximate centre of the radiant surface, while those caused by borehole fracturing extended in a radial pattern centred on the borehole. With increasing irradiation time, the primary cracks gradually extended to the four side surfaces perpendicular to the surface irradiated by microwaves along the side boundaries of the samples. The applied unidirectional stress promoted fracturing: network-shaped cracks extended on the two end surfaces perpendicular to the loading direction, while primary shear cracks appeared on the four side surfaces parallel to the applied loading direction. The surface irradiated by microwaves exhibited surface exfoliation and, with increasing stress, the irradiated surface showed an increased area of exfoliation. After microwave treatment, the P-wave velocity of the samples decreased to a certain extent and the reduction in P-wave velocities along the direction of microwave treatment was more significant than that along the other two directions. Moreover, the longer the irradiation time, the larger the reduction in P-wave velocity. The results of field testing revealed that the borehole fracturing mode exhibited a favourable fracturing effect on boreholes in rocks. The sound velocity around the borehole and between the boreholes both declined to some extent.

By investigating the fracturing effect on basalt, crack propagation, and the P-wave velocity, it can be speculated that the two rock fracturing modes both have a favourable effect, implying that the OMWFA is theoretically and practically feasible. Owing to it is unrestricted by microwave cavities, the test apparatus can be used to fracture large-size rocks and engineering-scale rock masses through microwave treatment. The surface and borehole fracturing modes separately contribute to microwave-assisted mechanical rock breakage and stress release in the rock masses typically encountered in deep underground engineering operations. This is significant to those seeking to realise the engineering application of microwave-induced hard rock fracturing technology.

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