Simulation Study of Rock-breaking Efficiency of Microwave-assisted TBM Disc cutters

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Abstract: The research through the establishment of microwave-assisted disc cutter rock-breaking discrete element model, from the perspective of rock-breaking specific energy to analyze the change rule of disc cutter rock-breaking efficiency before and after microwave radiation. The results show that: in the cutter spacing 180mm range, the rock-breaking specific energy before and after microwave radiation with the increase of the cutter spacing show a "first decrease and then increase" trend, when the cutter spacing 90mm, to reach the minimum rock-breaking specific energy; through the comparison, the microwave radiation to improve the rock-breaking efficiency of the disc cutter is effective, it is recommended to choose the spacing of 150mm waveguide and disc cutter for joint rock-breaking.

Keywords**:** microwave-assisted rock-breaking; disc cutters; discrete element; specific energy

1. Introduction

Microwave-assisted disc cutter breaking method effectively addresses issues such as reduced tunneling efficiency, prolonged construction time, and increased total economic investment due to disc cutter wear [1]. Consequently, researchers have shown significant interest in studying microwave-assisted disc cutter breaking.

Numerous scholars have carried out a lot of research on the damage mechanism of microwave-assisted rock breaking, in which intrinsic factors such as mineral species, mineral particles and pore water were analyzed. Lu et al. [2], and Gao et al. [3] explored the dynamic response of different rock minerals to microwave radiation, identifying mineral groups, crystal structure, and iron content as the primary factors influencing the heating rate of rock minerals. Wang et al. [4] and Xue Botian [5] analyzed and revealed that the weakening effect of microwave irradiation on rocks is positively correlated with the mineral grain size ratio. Furthermore, Zhao et al. [6], and Hartlieb et al. [7] study shows pore water can promote microwave disruption. External conditions, such as microwave power and radiation time, and surrounding pressure, also exert varying degrees of influence on microwave heating characteristics and rock damage. For example, Lu et al. [8], and Pressacco et al. [9] analyzed the distribution characteristics of rock cracks under microwave radiation and found that the number and depth of cracks were positively proportional to the microwave radiation time Li et al. [10], and Ge et al. [11] found that higher microwave power and longer irradiation time promote heating rates and crack damage in rocks. Lu et al. [12] and Feng et al. [13] explored the effect of surrounding pressure on crack expansion in rocks under microwave radiation, revealing that surrounding pressure inhibits microwave cracking.

Existing researches mainly analyze the damage destruction mechanism of microwave radiation on rock, while less research on the efficiency of microwave and disc cutter joint rock-breaking. This study establishes a microwave-assisted TBM disc cutter rock-breaking model, explores and analyzes the change rule of disc cutter rock-breaking efficiency before and after microwave radiation, and puts forward feasible optimization suggestions.

2. Numerical simulation analysis

2.1 Numerical modeling

The microwave-assisted disc cutter rock-breaking model constructed according to the existing research results is shown in Figure 1. The main parameters of the model, as shown in Table 1. Simulation of assisted rock breaking studies using waveguides and disc cutters with the same spacing (60 mm, 90 mm, 120 mm, 150 mm, and 180 mm). The confining pressure and the penetration rate of the disc cutter were set to 5 MPa and 0.1 m/s, respectively, and the rock-breaking mode used the disc cutters penetrating sequentially to analyze the rock-breaking specific energy (1# disc cutter penetrating first, 2# disc cutter penetrating later), as shown in Figure 2.[14]

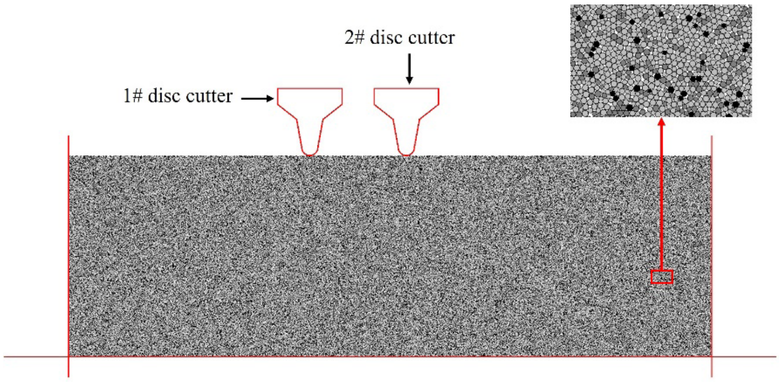

Figure 1. Rock-breaking model with disc cutters [14]

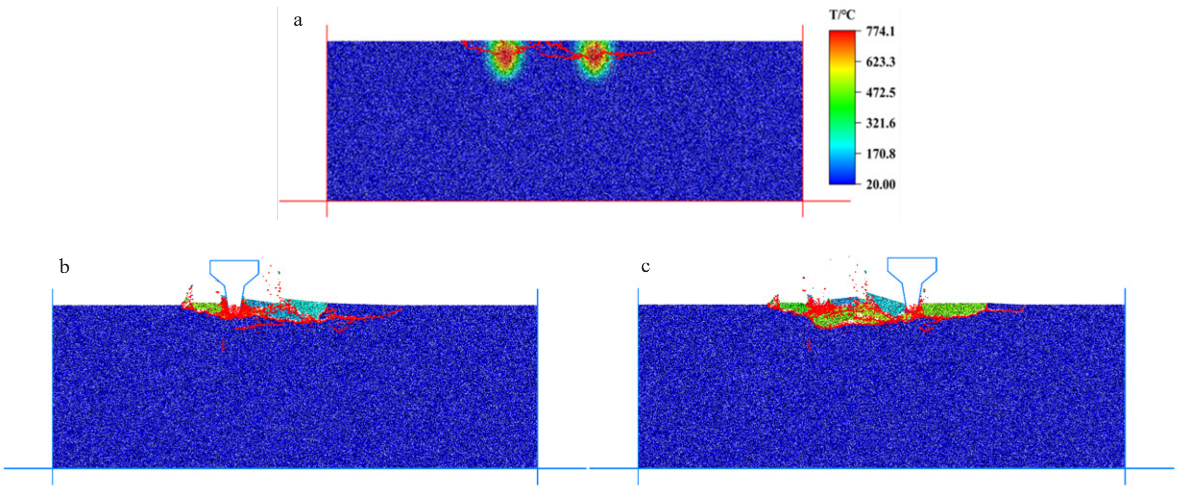

Figure 2. Rock Breaking Effect at Cutter Spacing 150mm after Microwave Radiation [14]

Table 1. Microscopic parameters of granite model [14]

Model variable	Feldspar	Diopside	Biotite
Minimum particle radius/mm	0.5		
Particle size ratio	1.66		
Particle density/kg·m^{-3}	2750	3560	3080
Parallel bonding normal strength/MPa	108.8±5		
Tangential strength of parallel bonding/ MPa	112.5±5		
Thermal expansion coefficient/(10^{-6})	4.8	6.5	8.3
Thermal conductivity/(W/(m·°C))	2.31	5.76	1.17
Specific heat capacity/(J/(kg·°C))	710	800	760

2.2 Analysis of rock-breaking efficiency

$$S_e = \frac{W}{V} = \frac{\sum_{i=1}^{n} F_v(i) \cdot d(i)}{V} \tag{1}$$

Where W is the rock-breaking energy of the disc cutter; V is the rock-breaking volume; n is the analysis step; $F_v(i)$ is the average value of the normal force of the disc cutter; $d(i)$ is the normal displacement.

$$\text{Rock-breaking specific energy reduction} = \frac{S_e(p,90) - S_e(p,s)}{S_e(p,90)} \times 100\% \tag{2}$$

Where $S_e(p,90)$ is the specific energy at the penetration of p mm and cutter spacing of 90 mm before microwave radiation; $S'_e(p,s)$ represents the specific energy at the penetration of p mm and cutter spacing of i mm after microwave radiation (p={4,6,8,10,12}; s={60,90,120,150,180}).

Calculate the rock breaking specific energy according to Eq.(1), and draw the variation of rock breaking specific energy under different combinations of penetration and cutter spacing, as shown in Figure 3. The rock-breaking specific energy before and after microwave radiation has the same trend, with the increase of cutter spacing, the specific energy firstly decreases and then rises, and the rock-breaking specific energy reaches the lowest when the cutter spacing is 90mm. Before microwave radiation (Figure 3(a)), Specific energy varies from 35.48 $MN\cdot m^{-2}$ to 118.56 $MN\cdot m^{-2}$ within cutter spacing 180 mm and penetration 12 mm. For cutter spacings 90 mm, 120 mm, 150 mm, and 180 mm, the average specific energies at penetration 12 mm are 37.79 $MN\cdot m^{-2}$, 65.04 $MN\cdot m^{-2}$, 107.87 $MN\cdot m^{-2}$, and 114.11 $MN\cdot m^{-2}$, respectively, reflecting increases of 72.11%, 65.85%, and 5.78%. This indicates that before microwave radiation, specific energy increases with cutter spacing, stabilizing after spacing 150 mm. Conversely, after microwave radiation (Figure 3(b)), Specific energy varies from 2.51 $MN\cdot m^{-2}$ to 18.37 $MN\cdot m^{-2}$ within cutter spacing 180 mm and penetration 12 mm. For cutter spacings 90 mm, 120 mm, 150 mm, and 180 mm, the average specific energies are 3.75 $MN\cdot m^{-2}$, 5.35 $MN\cdot m^{-2}$, 6.00 $MN\cdot m^{-2}$, and 15.01 $MN\cdot m^{-2}$, respectively, with increases of 42.67%, 12.15%, and 150.17%. This indicates that the specific energy change is relatively stable in the cutter spacing from 90mm to 150mm, while the cutter spacing is larger than 150mm. Microwave radiation is used as an aid to rock breaking, so it is more meaningful to compare the specific energy of by comparing before and after microwave radiation. The effect of microwave-assisted rock breaking was analyzed by taking the specific energy with cutter spacing 90 mm before microwave radiation as a benchmark. The percentage weakening of rock breaking specific energy after microwave radiation is calculated from Eq. (2) and the results are shown in Table 2.

From Table 2, it can be seen that the microwave-assisted effect is significantly smaller at cutter spacing 180 mm compared to the weakening effect in the range of cutter spacing 150 mm. Although Figure 3(b) indicates very low specific energy at cutter spacing 90 mm after microwave radiation, Table 2 reveals that the differences in specific energy between 150 mm and 90 mm, for penetration depths of 4 mm, 6 mm, 8 mm, 10 mm, and 12 mm, are as follows: 8.36%, 6.35%, 6.11%, 4.24%, and 5.04%. Consequently, a cutter spacing of 150 mm offers a reduction in the number of disc cutters and the associated economic investment, aligning better with the practical requirements of engineering applications.

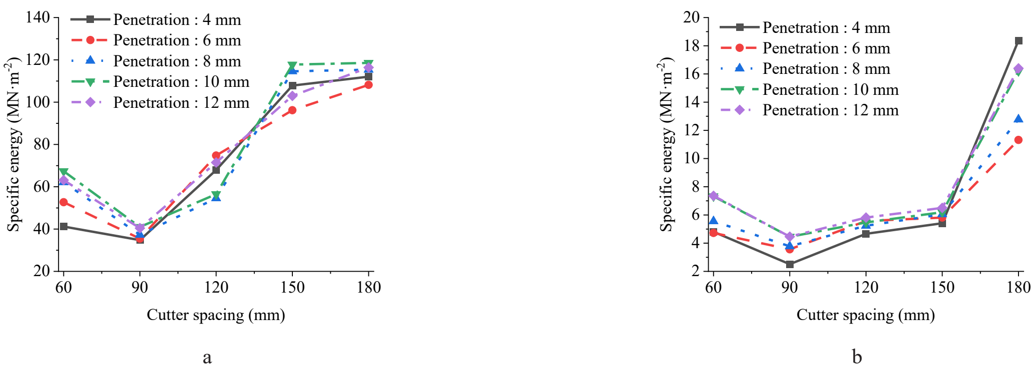

Figure 3. Variation of specific energy with penetration and cutter spacing: (a) Before microwave radiation; (b) After microwave radiation

Table 2. Decrease in specific energy of disc cutters

Penetration	Cutter spacing				
	60mm	90mm	120mm	150mm	180mm
4mm	86.17%	92.79%	86.59%	84.43%	47.18%
6mm	86.69%	89.96%	84.30%	83.61%	68.09%
8mm	82.10%	89.87%	85.96%	83.76%	65.74%
10mm	82.13%	89.12%	86.65%	84.88%	60.47%
12mm	81.81%	88.97%	85.63%	83.93%	59.46%

3. Conclusions

Discrete elements are used to construct a microwave-assisted disc cutter breaking model to investigate the changes in the effect of microwave radiation on the efficiency of disc cutter breaking, and the main conclusions are as follows:

(1) Before and after the microwave radiation, the rock-breaking specific energy of the disc cutter penetrating in sequence with the increase of the cutter spacing are showing the first decline and then rise rule of change, when the cutter spacing of 90 mm, the rock-breaking specific energy reaches the minimum.

(2) Microwave radiation can significantly reduce the rock-breaking specific energy and improve the rock-breaking efficiency. In the range of cutter spacing of 180 mm, the average normal force weakening effect of microwave radiation on the disc cutter when it penetrates in sequence is more than 59.46%.

(3) Considering the comprehensive rock-breaking efficiency, it is recommended to choose the spacing of 150mm waveguide and disc cutter for joint rock-breaking.

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