EXPERIMENTAL STUDY ON CHARACTERISTIC AND MECHANISM OF SIMULATED LUNAR ROCK DESTRUCTION UNDER HIGH ENERGY LASER IRRADIATION

by

Xue-Min ZHOU [a],Chuo ZHANG [b*], Jun-Jun LIU [c],Hai-Chun HAO [a], Zheng GAO [a], Yan WU [a], Qiu-Yue LI [d], Xiang-Yue WEN [a], Xuan WANG [a], Zhao-Ying YANG [a]

[a] Institute of Deep Earth Sciences and GreenEnergy, College of Civil and Transportation Engineering,Shenzhen University, Shenzhen 518060, China

[b] Sichuan Shengtian New Energy Development Co., Ltd.,Chengdu, 610229,China

[c] College of Water Resource and Hydropower, State Key Lab. of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China

[d] Jinshi Drilltech Co. Ltd., Tangshan 063004, China

The large load and poor heat dissipation of moon rock core drilling leads to the difficulty of rock breaking and low drilling and sampling efficiency. As a new auxiliary rock breaking method, laser rock breaking is expected to be applied to perturbation sampling in lunar rock drilling. Revealing the fracture characteristics and mechanism of rock under laser irradiation is an important basis for realizing laser-assisted lunar rock sampling. Basalt was used as simulated lunar rock sample, and its mechanical response characteristics under laser irradiation were analyzed from macro to micro point of view, and the failure law under different laser power and different irradiation time was explored. The results show that the failure of the sample under laser irradiation is mainly characterized by local rock melting and dynamic crack propagation, and the surface temperature of the sample follows the characteristics of Gaussian distribution. The laser power has a greater influence on the degree of rock weakening than the irradiation time. Laser irradiation of rocks can significantly reduce rock strength, and has obvious effects on improving rock breaking efficiency and reducing in situ disturbance. It is expected to provide theoretical and technical support for assisting lunar rock drilling and sampling in the future.

Key Words: *Laser irradiation, Simulated lunar rock, Temperature field, Failure characteristic, Crack propagation*

Introduction

The moon is the closest celestial body to us and has rich mineral resources and space resources. It is the first choice for deep space exploration, and the rapid rock fragmentation and sampling is our primary task [1-4].Many countries have made great progress in their lunar exploration programs[5-7]. However, unlike drilling and sampling on Earth, the low gravity and vacuum environment of the moon require higher drilling methods and equipment [8]. Due to the current technical limitations and the complex environment of the moon, the drilling depth of lunar soil and lunar rock

* Corresponding author; e-mail: zhangchuo@scshengtian.com

sampling is very limited, and the sampling range is also small[9]. The difficulty of rock breaking, low efficiency, and large disturbances in the drilling process cannot maintain the in situ characteristics of the rock in the lunar environment are the two major problems of lunar rock sampling at present.

In order to achieve the efficient and micro-disturbance sampling of unmanned drilling of lunar rock, it is urgent to innovate the drilling method and develop efficient drilling advanced drilling equipment. For this reason, some scholars put forward the idea of jet, microwave[10-12] , laser and other new means to assist in mechanical breaking of hard rock, and carried out a series of beneficial research.Laser as a monochromatic and directional high energy density beam is widely used[13,14].Laser rock breaking technology has been widely concerned by scholars due to its attractive prospect of low cost, high efficiency and high reliability, and has become a research hotspot in recent years[15].Yang et al[16]carried out the hard rock breaking experiment with fiber laser and described the evolution process of laser perforation in detailToshio et al[17]studied the mechanism of borehole rupture by fixed and moving lasers.Pan et al[18] studied the influence of laser irradiation parameters on the special fracture characteristics of shale.Chen et al[19] found that the penetration rate of elliptical laser assisted bit drilling is 61% higher than that of conventional non laser drilling.

Based on the above research, the local high temperature generated by laser irradiation of rock can cause thermal fracture and melting of rock, destroy the original structure of rock, and cause cracks, thus significantly reducing the strength of rock and improving the mechanical drilling rate. Thus, laser rock breaking technology is expected to be applied to the sampling process of lunar rock drilling to improve the sampling efficiency and reduce the disturbance of surrounding rock. Taking basalt as the simulated lunar rock, the mechanism of laser rock interaction is explored from macro and micro scales, and the characteristics and laws of its failure response under laser irradiation with different parameters are studied, so as to reveal the fracture and weakening mechanism of rock samples under laser irradiation, and provide theoretical and technical support for assisting lunar rock perturbation drilling and sampling.

Moon-based Simulated Sample Preparationand Experimental Setup

Sample preparation

The formation process of lunar sea basalt is similar in chemical composition to that of Earth basalt, formed by the condensation of lava sprayed from the deep part of the moon to the surface of the moon. It is mainly composed of plagioclase, pyroxene and peridot, and the physical and mechanical properties are similar to those of the Earth's basalt. Therefore, Shanxi Zuoquan basalt was selected as the simulated lunar rock to explore its destructive characteristics and failure mechanism under the action of high-energy laser.According to the production requirements of standard rock samples, it is prepared into cylindrical standard samples with Φ50mm×100mm specifications.

Fig. 1 Sample preparation

Experimental setup

The experiment is mainly completed by the laser precise rock breaking system of the research group, and the microscopic analysis is carried out in combination with scanning electron microscope (SEM)and other test methods. The experiment equipment and process are shown in Fig. 2. First, turn on the water cooler, laser and other auxiliary test equipment in turn.Adjust the temperature and video monitoring window to the appropriate position, place the sample to the predetermined position and adjust the laser parameters. Then, turn on the laser shielding gas, start recording and emitting the laser, stop the laser emission when the predetermined time is reached, turn off the shielding gas, stop recording and save the file. Repeat the above steps until all samples have completed the laser action. Finally, use the 3D profilometer to scan the surface of the sample, cut the damaged area of the sample for SEM test.

In order to obtain the failure behavior of basalt under laser irradiation with different parameters and study its fracture law and failure mechanism, we designed two groups of tests. The experimental scheme is shown in Table 1. The distance between the laser head and the rock sample surface is kept at 13.5cm in both groups of tests. The continuous laser beam is used to measure the initial spot diameter of the laser irradiated to the rock sample surface is about 4mm. The schematic diagram of rock damage by laser radiation is shown in Fig. 3.

Table 1Experiment scheme

group	I						II				
number	I-1	I-2	I-3	I-4	I-5	I-6	II-1	II-2	II-3	II-4	II-5
irradiation time/s	5	10	15	20	25	30	30	30	30	30	30
laser power/W	500	500	500	500	500	500	250	500	750	1000	1250

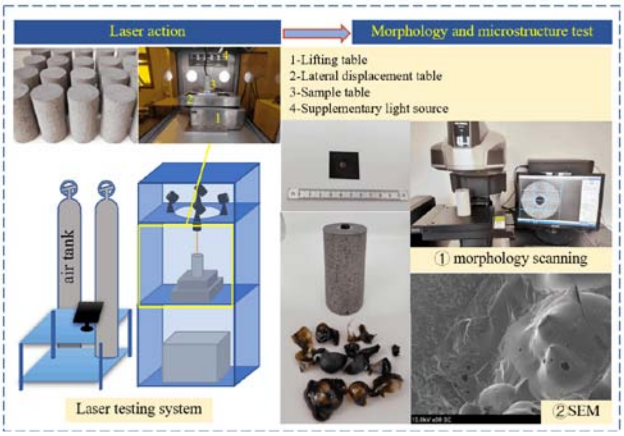

Fig. 2 Experiment equipment and process

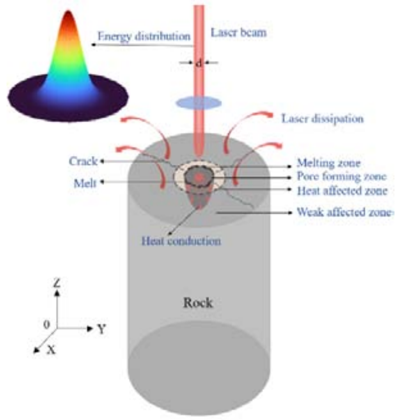

Fig. 3 Schematic diagram of rock damage by laser radiation

Temperature field evolution of the basalt surface under laser irradiation

The melting point of basalt is 1500-1600 °C, so infrared thermal imaging cameras with a measuring range of 900-2450 °C are used to record the temperature changes of the rock in the high temperature section.

Fig. 4 is a temperature cloud corresponding to different times when the 500W laser irradiates the rock sample. The temperature evolution curve is drawn by extracting pixel points from the temperature cloud map, as shown in Fig. 5. It can be seen that after laser irradiation, the temperature distribution of basalt surface basically follows the Gaussian distribution. The temperature rise area is mainly concentrated in the laser irradiation area, and its temperature is much higher than that of the non irradiation area. With the increase of the distance from the center point, the temperature decreases rapidly, and then it slows down. And in the initial 1s, the surface temperature of the rock sample changes greatly, the temperature of the center point increases, and the influence range expands. After 1s, the surface temperature distribution of the rock sample decreases gradually with the change of time. At 5s, the surface temperature field of the rock sample reaches a basically stable state.

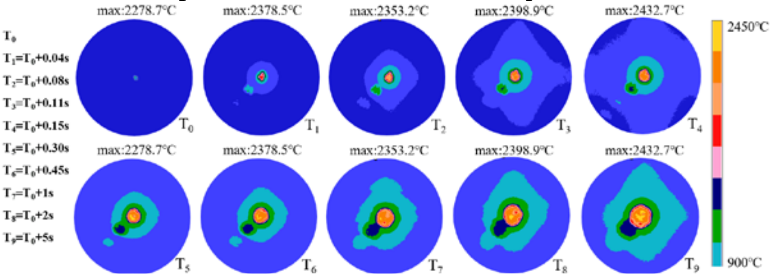

Fig. 4 Temperature evolution cloud under 500W laser irradiation

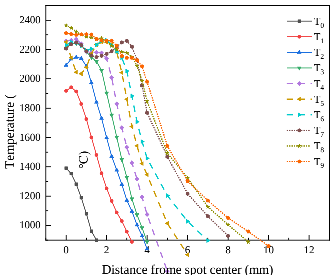

Fig. 5Temperature evolution curve under 500W laser irradiation

Fig.6 shows the temperature cloud of the rock sample surface at the same time of laser irradiation under different laser power, and the temperature evolution curve is drawn by extracting pixels from it, as shown in Fig.7.It can be seen that the higher the laser power is, the higher the central point temperature captured at the initial time is, and the larger the area of high temperature area on the surface of the rock sample is.This is because the laser power directly determines the energy density of the laser beam. With the increase of the laser power, the energy density of the laser beam increases, so that the energy absorbed by the rock sample increases, and the overall energy accumulation of the rock sample is affected. As a result, the temperature at the same position of the rock sample rises, which affects the rock breaking effect.At the same time, with the increase of laser irradiation time, the energy accumulation will also increase, which will affect the surface temperature distribution of rock samples.

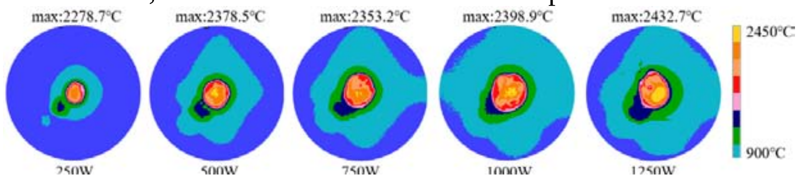

Fig. 6Temperature distributioncloud after 10s irradiation with different power lasers

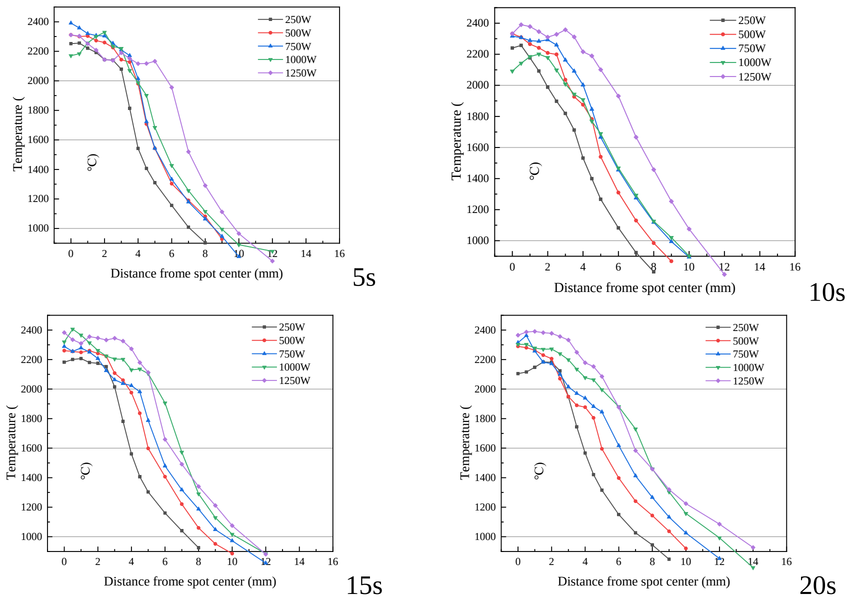

Fig. 7Temperature distribution at each time under different power laser irradiation

Fracture damage characteristics of basalt under laser irradiation

Macroscopic fracture damage characteristics of basalt under laser irradiation

According to the results recorded by the imaging camera, when the laser starts to act on the rock surface, the laser irradiation area will produce violent reactions. The rock gradually melts and forms a flowing dark brown melt. When the laser stops irradiation, the melt rapidly condenses and expands. According to the surface topography characteristics of rock samples, the surface topography of rock samples after laser irradiation can be divided into four areas: hole forming zone, melting zone, heat affected zone and weak affected zone.And the surface morphology of rock samples has a good correspondence with the temperature cloud. The hole forming zone is the part of the hole formed by rock melting, and the corresponding temperature is above 2000℃ . The melting zone is the part close to the surface of the hole, with the melt attached, and the corresponding temperature range is 1600 ℃ - 2000 ℃. The heat affected zone is about 3-5mm outward from the melting zone, and the corresponding temperature range is 1000℃ - 1600 ℃. The weakly affected zone is far away from the laser irradiation area and near the edge of the rock sample, and the temperature is below 1000 ℃.

Fig. 8 is the surface topography of rock sample after 500W laser irradiation for different times. Where (a'- f') is the surface topography after removing the melt. With the increase of laser irradiation time from 5S to 30s, the hole of basalt become larger, the rock samples remain intact, and no significant cracks are observed.This is because the basalt is hard and strong, and the adhesive force between the mineral molecules of the rock is large. The thermal stress generated by laser irradiation is not enough to resist the strength of the rock, and it is bound by the mineral matrix, which mainly presents melting failure.

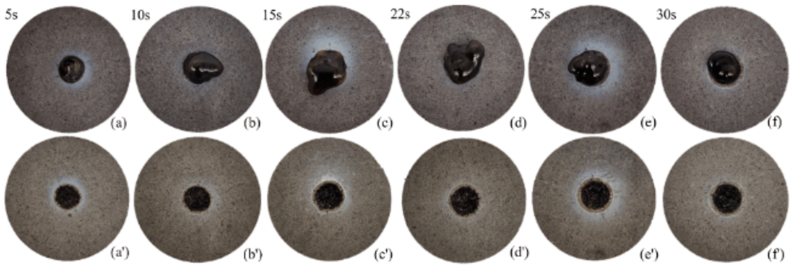

Fig. 8Rock morphology after laser irradiation for different time(a-f: before removing melt; a'-f':after removing the melt)

The surface morphology of the rock sample after the same time of laser irradiation with different powers are shown in Fig. 9. With the increase of laser power from 250W to 1250W, the hole becomes larger and the melt increases. When the laser power reaches 1000W, two tiny cracks can be observed, and after irradiation with 1250W laser for 30s, three obvious cracks can be observed. It is speculated that with the gradual increase of laser power, temperature level and thermal stress, the binding of mineral matrix is broken, and the expansion and extrusion of high-temperature melt are superimposed, so that the original tiny voids expand and finally form cracks. And the larger the laser power, the more the number of cracks and the larger the crack opening.

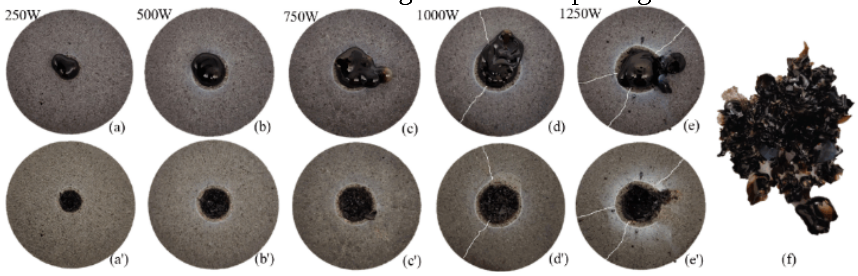

Fig. 9Rock morphology at different irradiations power(a-f: before removing melt; a'-e':after removing the melt; f: the melt)

Microscopic damage characteristics of basalt under laser irradiation

The pore forming zone, melting zone, heat affected zone and weakly affected zone of the rock sample after laser irradiation are observedthrough scanning electron microscope (SEM), as shown in Fig. 10.The surface of the pore forming area is completely covered by the melt, and obvious fracture cracks and holes can be observed, which is caused by uneven thermal stress. There are a large number of holes and bubbles at the junction of the melting zone and the heat affected zone, and the melt flows outward to form a river like texture. The rocks in the heat affected zone are not melted, but some minerals are decomposed under the action of high temperature, and the water evaporates, forming a large number of irregular voids and rough surfaces. Along with the thermal damage and fracture of the rocks, some belt shaped fracture zones and a large amount of rock debris and powder appear. The composition and structure of the weakly affected zone are relatively uniform, the particles are fine, there are a few micro scale voids, and no obvious cracks are found.

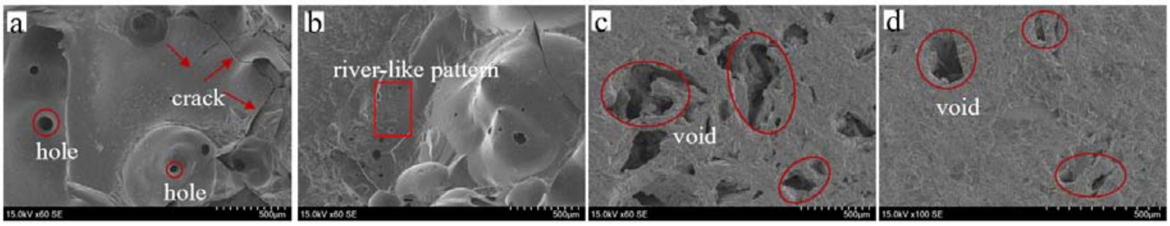

Fig. 10SEM images of different areas on basalt surface after laser irradiation (a:hole forming zone(attachments in the hole);b: melting zone; c: heat affected zone; d: weak affected zone)

Rock breaking efficiency of basalt under laser irradiation

Specific energy (SE) and rate of perforation (ROP) are important parameters for analyzing the degree of rock fragmentation, which show the effect of laser on rock to a certain extent. Where SE represents the energy consumed to remove the unit volume, ROP represents the drilling depth per unit time[20]. The Specific energy SE can be expressed as

$$SE = \frac{Pt}{V} \quad (1)$$

where P is the average laser power, and t is the irradiation time. The volume V of rock removed can be expressed as

$$V = \frac{m_1 - m_2}{m_1} \cdot V_0 \quad (2)$$

where m_1 is the mass of rock sample before test, m_2 is the mass of rock sample after test, and V_0 is the initial volume of rock sample. The rate of perforation ROP reads

$$ROP = \frac{h}{t} \quad (3)$$

where h is perforation depth and t is the irradiation time.

Use 3D profilometer scanthe sample to obtain hole surface data, and calculate SE and ROP based on this, as shown inFig. 11. According to Fig. 11-(a), under the same conditions, the SE gradually increases with the increase of laser irradiation time, while the ROP basically shows a linear decreasing trend.It indicates that under this condition, the laser rock breaking efficiency is the highest at 5s, and the longer the laser irradiation time, the more laser energy is wasted, which is not conducive to the improvement of rock breaking efficiency. This is because the energy density of 500W laser is relatively low. When it is irradiated on the rock, the thermal energy converted by light energy just supports the physical state transformation of the rock surface. After that, a large amount of energy is used to maintain the state of its molten material. The energy absorbed by the surrounding and the rock at the bottom of the hole through heat conduction is insufficient to support its melting. The volume change of the removed rock is weak, and the rock breaking efficiency is reduced. It can be seen from Fig. 11 -(b) that with the increase of laser power, Se increases first and then decreases, while ROP keeps increasing. At 1250W, the ROP reaches the maximum value but SE is low, and the laser rock breaking efficiency reaches the maximum.On the whole, the SE of basalt is large after laser irradiation, and the ROP is low.This is due to the hard texture of basalt, which basically shows melting failure after laser irradiation, resulting in low rock breaking efficiency.

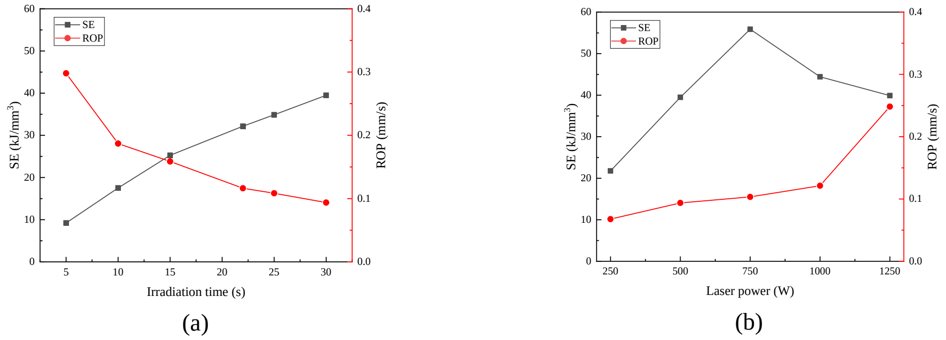

Fig. 11 Variation curves of SE and ROP with different laser parameters (a: irradiation time; b: laser power)

Conclusions

Taking the laser drilling and rock breaking technology as the starting point, this paper conducts laser rock breaking experiments and micro-fine observation experiments with different parameters. The surface temperature of basalt under laser irradiation basically presents Gaussian distribution characteristics. The temperature in the central area of laser irradiation is higher, the central point expands outward, and the temperature decreases rapidly. The larger the laser power, the larger the influence range of the high temperature region. Basalt melts and breaks under laser irradiation, and macro cracks occur under high-power laser irradiation. With the increase of laser power, the number of cracks increases and the crack opening increases. Due to water vaporization and mineral expansion, there are a lot of holes and microcracks on the surface of basalt. Under laser irradiation, SE increases with the increase of laser irradiation time, while ROP decreases with it. Under low power laser irradiation, rock breaking efficiency decreases with time. With the increase of laser power, SE increases first and then decreases, and ROP keep increasing. Compared with the laser irradiation time, the laser power has a greater impact on the rock breaking effect.

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Nomenclature

P - leaser power, [W]
t - irradiation time, [s]
V - volume of rock removed, [cm^3]
m_1 - mass of rock sample before test, [g]
m_2 - mass of rock sample after test, [g]
V_0-the initial volume, [cm^3]
h -perforation depth, [mm]

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