

Article

Laser Irradiation on Limestone and Cracking: An Experimental Approach

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Abstract: Using mechanical drilling to obtain energy resources stored in deep and hard rock layers is becoming increasingly challenging. Therefore, laser irradiation has emerged as a new and promising drilling method. In this study, the effects of immersion conditions on rock-breaking by laser irradiation on the temperature, hole size, rock-breaking efficiency, and macro-fracture after laser irradiation were investigated. Furthermore, the mineral changes and thermogravimetric analysis of rocks were studied. As indicated by the results, the temperature area over 100 °C increases with the increase of irradiation time, and the temperature range of between 2.27 cm² and 13.20 cm² varies with the change of laser power at between 90 W and 135 W. The hole-diameter value of the soaked sample was smaller than that of the dried sample. In addition, the hole depth of the soaked sample reduced by 15% at a power of 90 W and 45% at a power of 135 W, compared with that of the dried sample. The value of the modified specific energy of the soaked sample increased, which was particularly noticeable at low power. The soaked sample had a larger effect on the rate of perforation at high power and a smaller effect at low power. The cracks on the surface of the rock samples became larger after being placed for one month. Fracture length increased from 0.61 to 5.09 mm for dried samples and from 2.24 to 8.7 mm for soaked samples at a laser power of 90 W. Fracture length increased from 6.30 to 9.85 mm for dried samples and from 9.04 to 11.38 mm for soaked samples at a laser power of 135 W. The soaked sample began to show differences when heated at 100 °C, which was caused by the evaporation of some free water molecules in the rock. The main weight loss temperatures of the samples occurred in the range of 640 °C to 900 °C.

Keywords: laser irradiation; surface morphology; soaked rock; thermogravimetry



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1. Introduction

With the exploitation of oil and gas resources, deep wells have served as one of the most important fields of oil-related industries [1,2]. However, the traditional rotary-drilling method relies on high drilling pressure, high torque, and high speed to increase the mechanical drilling speed, which results in serious wear and tear on the drilling tools [3,4]. This results in low drilling efficiency, long drilling cycles, and high drilling costs, which cannot meet the development needs of deep and even ultra-deep oil and gas fields [5,6]. In this context, new types of rock-breaking are urgently needed.

Laser irradiation is one of the new non-mechanical contact methods of rock-breaking [7–9]. The high-energy beam emitted by the laser is used to radiate the rock surface, and the temperature of the rock rises after absorbing the light energy [10,11]. The uneven thermal expansion inside the rock leads to the occurrence and expansion of cracks, which makes the rock crack under the action of thermal stress and facilitates subsequent drilling [12,13]. Laser irradiation technology has the characteristics of improving the porosity and permeability of the tunnel and its surrounding rock matrix and of regulating the geometric shape of the tunnel [14], as shown in Figure 1. It has a low drilling cost with high drilling efficiency and has unique advantages in various new rock-breaking methods [15–17].

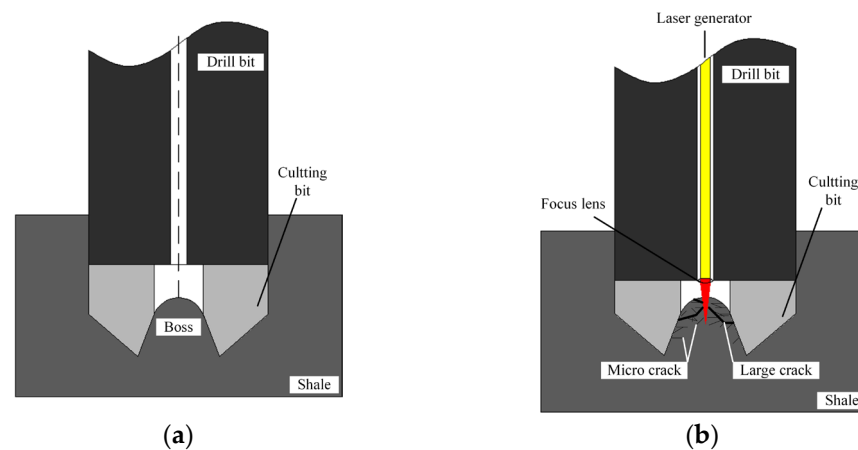


Figure 1. Schematic diagram for (a) drilling principle [18], and (b) laser-assist principle.

Research on the laser irradiation of rocks started in the 1960s, and can be broadly divided by research into two stages, including the rock-cutting stage of the low-power laser before 1994 and the drilling and rock-breaking stage of the high-power laser after 1994 [19]. In 1968, Moavenzadeh et al. [20] of the Massachusetts Institute of Technology proposed the idea of using the laser to break rock and drill at the 43rd SPE/ AIME autumn annual meeting. This was the first time that laser rock-breaking had been formally proposed. The Lebedev Institute of Physics, the military laser research center of the Soviet Union, followed closely and carried out research, achieving results on the irradiation of rocks with kilowatt-level lasers from 1968 to 1978 [21]. Bazargan et al. [22] compared laser drilling with other drilling techniques and investigated the effect of lasers on 13 different rock types. O'Brien et al. [21] carried out the feasibility experiment of laser irradiation on rock, which proved that rock-breaking by laser irradiation is superior to mechanical drilling in efficiency. Batarseh et al. [23] studied the interaction between high-power lasers and rock and the effect of lasers on rock porosity, permeability, strength, and other properties, and pointed out the application advantages of lasers in the oil and gas industry. Gahan et al. [24] used a 1.6 kW laser to irradiate dry sandstone and water-saturated sandstone. The results of the study indicated that the existence of water would make the experimental effect change more obviously. Xu et al. [25] examined the influence of different parameters on rock-breaking by laser irradiation through laboratory experiments. Batarseh et al. [26] conducted field experiments with laser techniques and showed that lasers could improve the permeability of the hole and its surrounding rock matrix, making it easier for oil and gas to enter the hole. Xu and Li et al. [27,28] found that the speed of rock-breaking by laser irradiation could reach about 105–115 m/h, which was ten times higher than that of traditional mechanical drilling. Pan et al. [29] studied that increasing the number of irradiated holes at high power is beneficial for crack extension under the condition of constant laser energy. Wang et al. [10] studied the effect of laser irradiation on the properties of rocks and showed that the fundamental factor leading to changes in the physical properties of rocks was the drastic change in the temperature field.

Heat transfer in laser irradiation can be described as a non-stationary heat transfer process of heat conduction, convection, and radiation [30]. Zhang et al. [31] combined an improved level-set method with a two-dimensional model simulating the laser punching process of a millisecond pulsed laser on an aluminium plate, using an equivalent specific heat capacity and a gas kinetic source term to model the phase transition. Ganesh et al. [32,33] obtained the fluid configuration and associated velocity field for a given timestep using the VOF method of tracking free surfaces and solved the energy equation as an advection diffusion equation using the control volume finite difference method. Kasimova et al. [34] employed the linear Stefan problem to model the phase transformation of limestone and sandstone after short-pulse laser irradiation. Damian et al. [35] used COMSOL multiphysics to study the heat transfer process during phase change in laser irradiation. Chen et al. [36]

simulated the generation and expansion of cracks under laser irradiation using PFC^{2D}. Ndeda et al. [37,38] used the finite element method to develop a numerical model of laser scattering in non-homogeneous granites to explain the presence of microfractures within the rock.

Rock fragmentation is becoming increasingly challenging in obtaining energy resources stored in deep and hard rock layers. Laser irradiation is a new drilling method with an appreciable prospect. The effects of laser parameters and rock properties on rock fragmentation were frequently heated in early studies; however, limestone thermal cracking by laser irradiation under immersion conditions has been studied in a few studies. In this study, the effects of immersion conditions on rock-breaking by laser irradiation on the temperature, hole size, rock-breaking efficiency, macro-fracture after laser irradiation, and fracture length were investigated. In addition, the changes in rock weight loss were determined by a temperature thermogravimetric analyzer. The results can be used to make a reference for the efficiency of rock crushing under laser-beam assistance and provide the experimental basis for the practical application of laser.

2. Experimental Procedure

2.1. Apparatus

The equipment of the experiment included a laser irradiation system and an infrared thermal imager, as shown in Figure 2. The laser irradiation system consisted of a fiber laser, host platform, refrigerator, three-axis mobile stage, display system, and computer control system, within the conditions of the infrared thermal imager with a temperature measurement range of $-40\text{ }^{\circ}\text{C}$ to $2000\text{ }^{\circ}\text{C}$, and a maximum frame rate of 200 Hz.

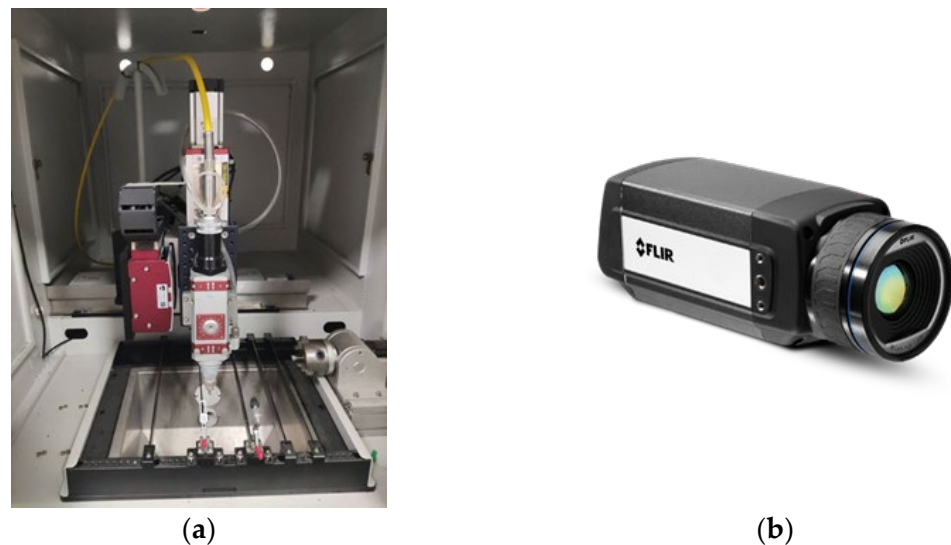


Figure 2. (a) Laser device; and (b) thermal infrared imager.

2.2. Experimental Scheme

The controlled variable method was used to study the cracking of the rock under different laser irradiation conditions. The mineral composition of limestone is shown in Table 1. Limestone was dried in an oven. Partially dried rocks were immersed in an airtight container and then placed in a natural environment for 24 h for laser experiments. The specific experimental scheme is shown in Table 2.

Table 1. Mineral composition of limestone.

Mineral Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO
Content /%	1.8	2.1	3.1	53.8	39.2

Table 2. Scheme of rock-breaking by laser irradiation.

	Laser Power/W	Irradiation Time/s	Specimen
Dried rock	90	90	1
		120	2
		150	3
		180	4
	135	90	5
		120	6
		150	7
		180	8
Soaked rock	90	90	9
		120	10
		150	11
		180	12
	135	90	13
		120	14
		150	15
		180	16

3. Results

A major advantage of rock-breaking by laser irradiation is the high energy density. The power determines the energy density, and irradiation time determines the interaction time between rock and laser, so power and irradiation time are important factors affecting the effect of rock-breaking by laser irradiation. Limestone is prone to fractures under natural conditions. These natural fractures are not only good oil storage structures but also water permeation channels. Therefore, the rock is often encountered in a wet state during drilling. The presence of water may change the properties of the rock, and it also could have a certain impact on the rock-breaking by laser irradiation, which requires special experimental analysis.

3.1. Temperature Distribution under Different Laser Power

During the experiment, the infrared thermal imager was used for real-time recording. The upper limit of temperature measurement of an infrared thermal imager is 2000 °C, and the recording frame rate is 6 Hz. To facilitate analysis, the video was saved every 180 frames (30 s). The selected samples were irradiated with a power of 90 W power for 180 s and 135 W power for 180 s, as shown in Figure 3.

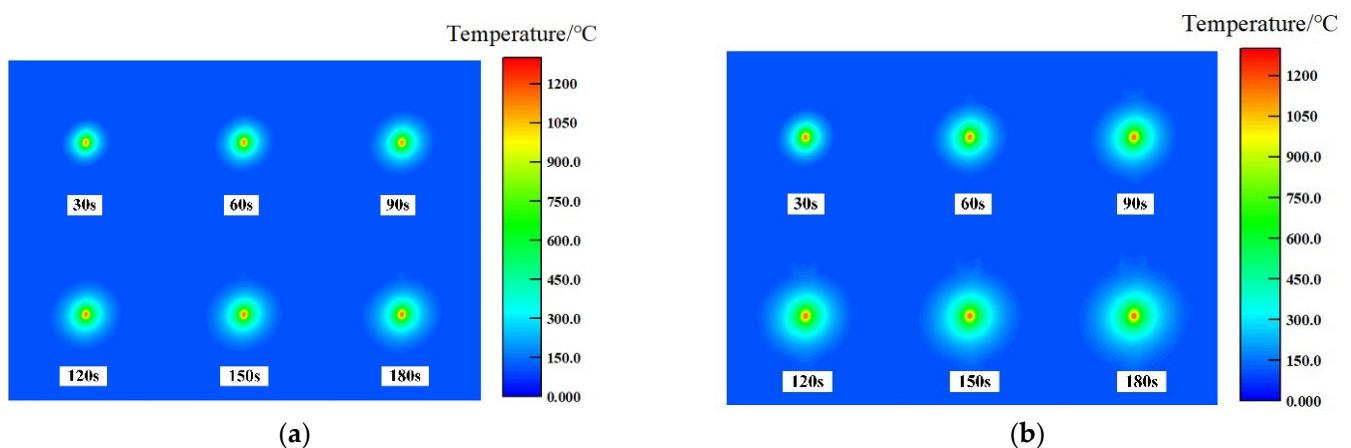


Figure 3. Temperature distribution after laser irradiation with different laser power (a) 90 W; and (b) 135 W.

Figure 3a shows the temperature distribution of the rock with the irradiation time from 30 s to 180 s at a laser power of 90 W. The irradiation area above 100 °C increases with the increase of irradiation time, and the maximum temperature of the rock remains above 1200 °C. Figure 3b shows the temperature distribution of the rock with the irradiation time from 30 s to 180 s at a laser power of 135 W. Compared with the power of 90 W, the irradiation area range above 100 °C is larger. This is because the higher the laser power for the same irradiation time is, the more energy the rock absorbed, causing more damage to the limestone sample.

Figure 4 shows the trend of the area of the temperature region (over 100 °C) with increasing laser irradiation time at different laser power. The high temperature area increases from 2.27 cm² to 7.07 cm² with the increase in irradiation time when the sample is irradiated with a power of 90 W. The high temperature area increases from 3.46 cm² to 13.20 cm² with the increase in irradiation time when the sample is irradiated with a power of 135 W. In addition, when the power is 90 W, the growth trend of the high-temperature region over 100 °C becomes slower after 90 s, while the high-temperature region still maintains a clear growth trend during the entire irradiation period at a power of 135 W. This is because the subsequent laser energy is almost completely dissipated or consumed in the repeated melting of the rock when the irradiation time reaches 90 s at a power of 90 W. For the power of 135 W, the time of 180 s has not reached equilibrium, and there is still a trend of continuous increase.

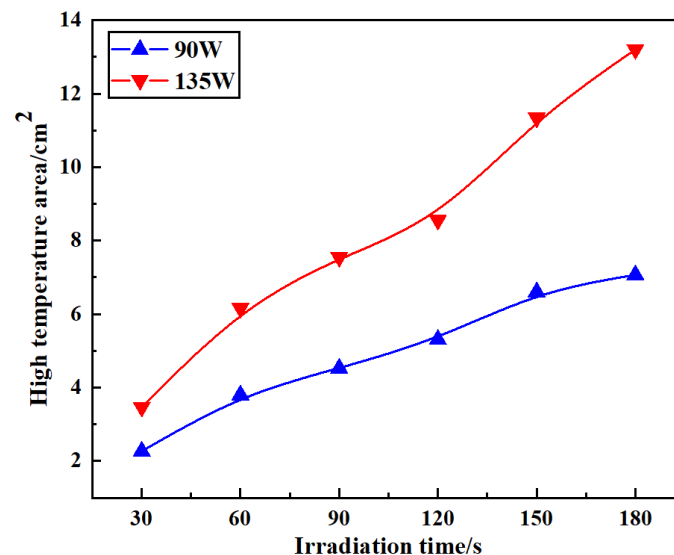


Figure 4. Variation of high temperature area with irradiation time.

3.2. Analysis of Hole Size

Figure 5a shows the changing trend of the hole diameter of the dried sample with the increase in irradiation time. The hole diameter increases from 2.25 mm to 2.70 mm with increasing irradiation time when the specimen is irradiated at a power of 90 W. The hole diameter increases from 2.73 mm to 2.98 mm with increasing irradiation time when the specimen is irradiated at a power of 135 W. Figure 5b shows the trend of hole diameter of the soaked sample with increasing irradiation time. The hole diameter increases from 1.95 mm to 2.39 mm with increasing irradiation time when the specimen is irradiated at a power of 90 W. The hole diameter increases from 2.65 mm to 3.07 mm with increasing irradiation time when the specimen is irradiated at a power of 135 W. It can be seen that the hole diameter of the specimen tends to increase with increasing irradiation time and power. In addition, the hole diameter value of the soaked specimen is smaller than the hole diameter of the dried specimen.

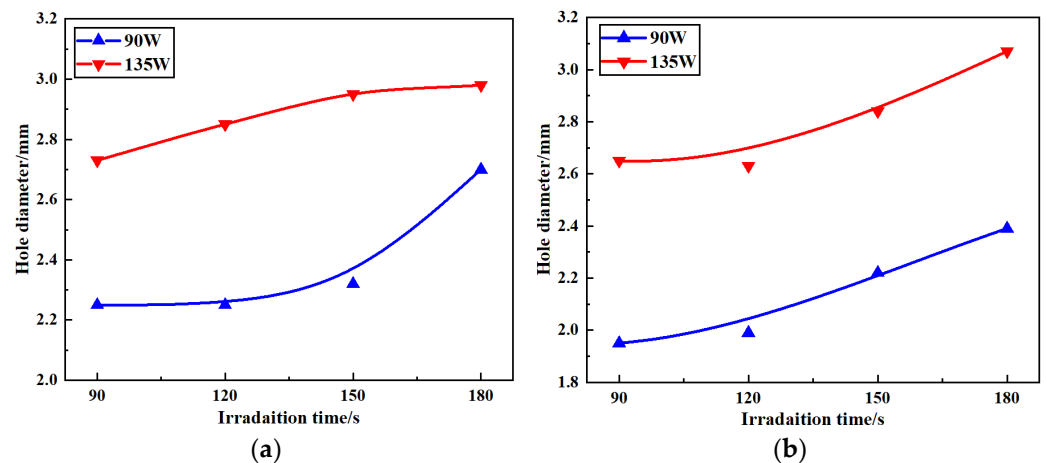


Figure 5. Variation of hole diameter with irradiation time under different conditions (a) dried sample; (b) soaked sample.

Figure 6a shows the changing trend of the hole depth of the dried sample with the increase in irradiation time. The hole depth increases from 2.68 mm to 4.02 mm with the increase in irradiation time when the specimen is irradiated at a power of 90 W. The hole depth increases from 7.20 mm to 9.21 mm with increasing irradiation time when the specimen is irradiated at a power of 135 W. Figure 6b shows the trend of hole depth of the soaked sample with increasing irradiation time. The hole depth increases from 2.90 mm to 3.02 mm with the increase in irradiation time when the specimen is irradiated at a power of 90 W. The hole depth increases from 3.88 mm to 5.02 mm with increasing irradiation time when the specimen is irradiated at a power of 135 W. It can be found that the reduction in hole depth of the soaked sample is 15% at a power of 90 W and 45% at a power of 135 W compared with that of the dried sample.

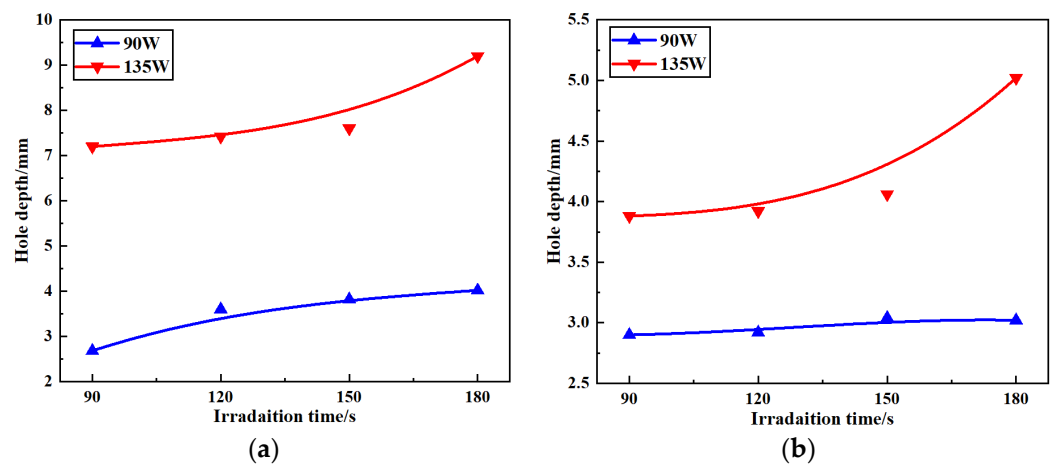


Figure 6. Variation of hole depth with irradiation time under different conditions (a) dried sample; (b) soaked sample.

Comparing Figure 5 with Figure 6, it can be found that increasing the laser power has a significant effect on the hole depth. This is because when the laser beam melts the rock and forms a hole, it loses direct contact with the surrounding solid rock, impeding the transfer of energy to the immediate vicinity, while maintaining a constant input of energy to the rock directly below. In addition, limestone is composed mainly of calcium carbonate, which is dense in composition. Calcium carbonate has a high melting point of 1340 °C but decomposes into calcium oxide and carbon dioxide at around 850 °C. The decomposition of calcium carbonate consumes a lot of energy and prevents the temperature of the nearby rocks from rising. Figure 7 shows the typical morphology of limestone pores after laser

irradiation. The presence of water reduces the hole diameter and depth and can increase the cost of drilling. In addition, water is involved in the chemical reaction of calcium carbonate at high temperatures.

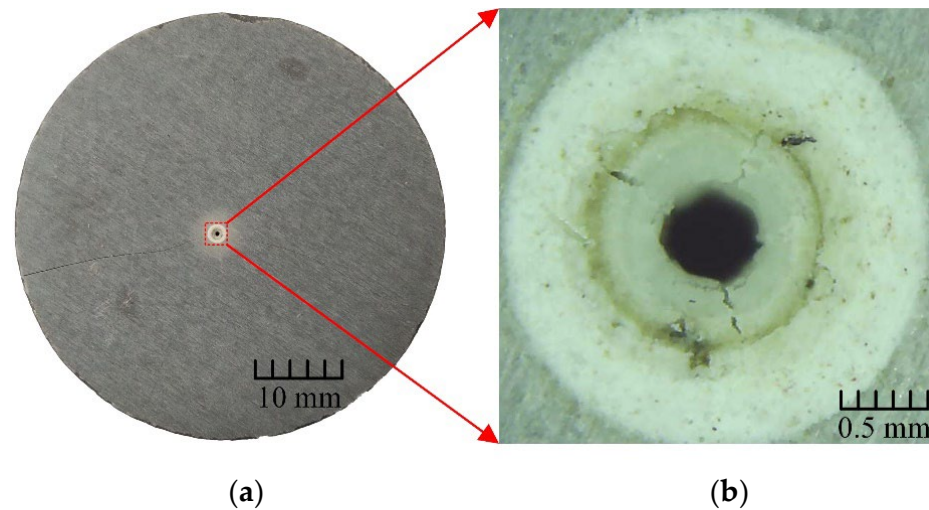


Figure 7. (a) Image of rock surface; (b) Magnified view of the small hole.

3.3. Efficiencies of Rock-Breaking under Laser Irradiation

Modified specific energy (*MSE*) is defined as the amount of energy required per unit mass of rock sample and is used in this study as a criterion to measure the efficiency of rock destruction, which can be expressed as [10,13]:

$$MSE = \frac{P * t}{m_R} \quad (1)$$

where m_R indicates the mass of rock removed. P is the power of laser irradiation (W), t is the irradiation time (s). A smaller value of *MSE* means that the same mass of rock requires less energy to break and is more efficiently broken.

In addition, the rate of perforation (*ROP*) is an important indicator of the effectiveness of laser rock-breaking. The formula for the rate of perforation is given:

$$ROP = \frac{\Delta l}{t} \quad (2)$$

where Δl represents the hole diameter. A higher value of *ROP* means that a deeper hole is formed at the same time and the rock is broken more effectively.

Figure 8 shows that the specimen has a larger *MSE* and a smaller *ROP* at a power of 90 W compared with 135 W, indicating that increasing the laser power improves the efficiency of rock-breaking. With the increase of the irradiation time, the *MSE* gradually increases, while the *ROP* gradually decreases. This indicates that the efficiency of rock-breaking by laser irradiation gradually decreases as the irradiation time increases. Meanwhile, the *MSE* value of the soaked sample increases, which is particularly noticeable at low power. The soaked sample has a large effect on *ROP* at high power and a smaller effect at low power. With the increase in irradiation time, *MSE* tends to increase gradually, which is caused by the laser repeatedly melting the rock debris at the bottom of the borehole. It is suggested that increasing laser power and timely removal of molten rock and debris can improve the energy use efficiency of rock-breaking by laser irradiation.

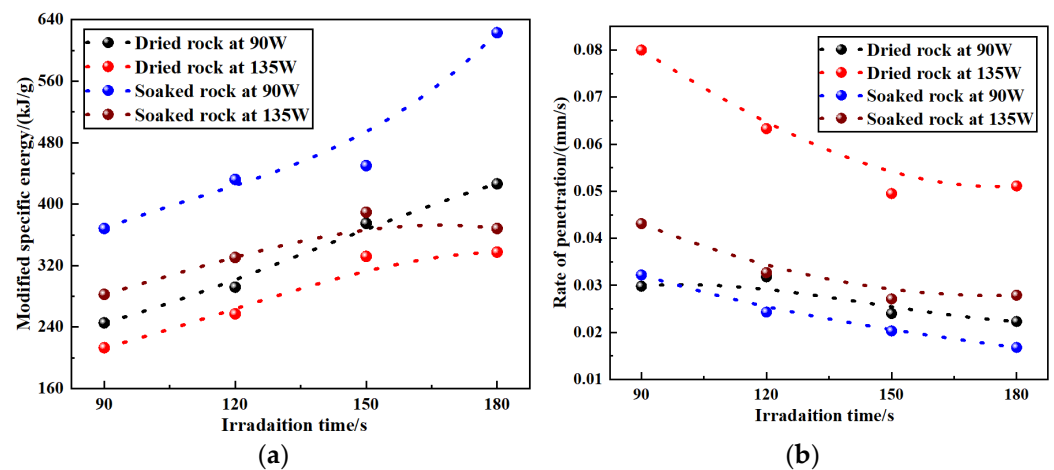


Figure 8. Plots of (a) modified specific energy versus irradiation time; (b) rate of perforation versus irradiation time.

3.4. Micro-Fractures after Laser Irradiation

Figure 9 shows the images of the surface of the dried sample after irradiation with the power of 90 W for 90 s, 120 s, 150 s, and 180 s (corresponding rock numbers are #1, #2, #3, and #4 respectively). It can be seen from Figure 9e–h that after the limestone is placed for one month, its cracks develop more obviously. Sample 1 has two outwardly extending cracks near the small hole, but not through the specimen. Sample 2 has one crack radiating outward to the edge of the rock surface. Sample 3 has two cracks extending to the edge of the rock surface, and the two cracks are in the same direction. Sample 4 has two cracks running through the rock surface, one of which turns at the edge. The cracks are developed after the specimens have been left for a while, and the cracks are more complex in specimens with long irradiation times.

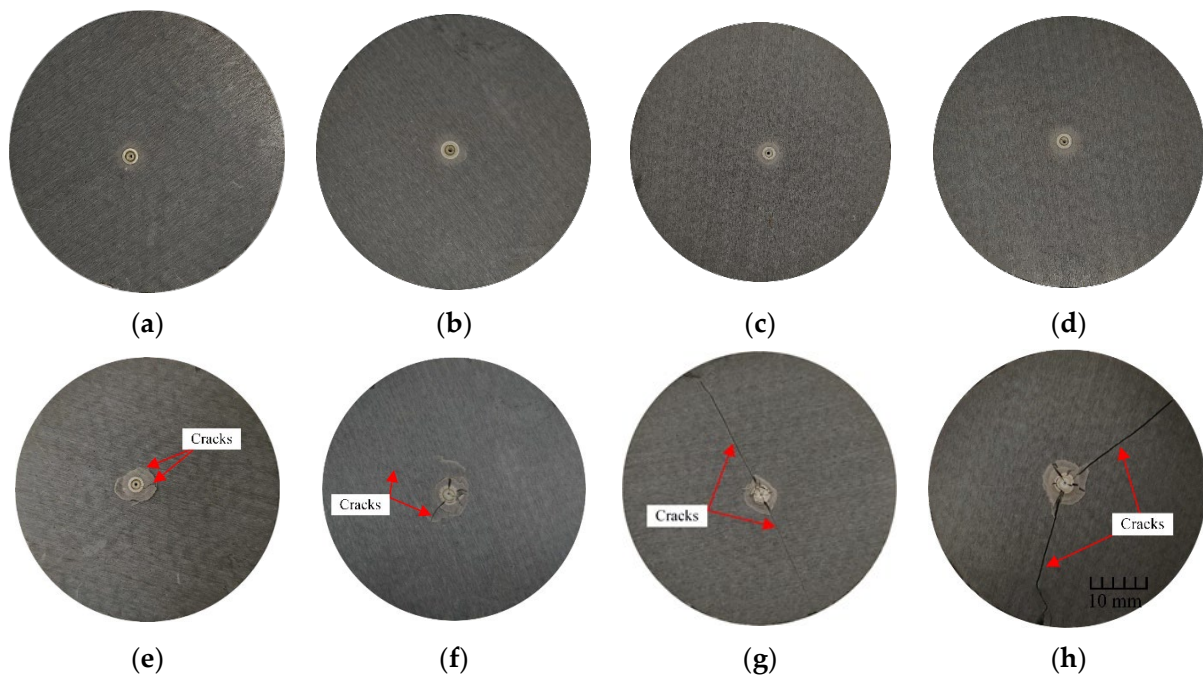


Figure 9. Surface morphology of dried sample after laser irradiation at a power of 90 W (a) 90 s; (b) 120 s; (c) 150 s; (d) 180 s; (e) 90 s after one month; (f) 120 s after one month; (g) 150 s after one month; (h) 180 s after one month.

Figure 10 shows the images of the surface of the soaked sample after irradiation with the power of 90 W for 90 s, 120 s, 150 s, and 180 s (corresponding rock numbers are #9, #10, #11, and #12 respectively). It can be seen from Figure 10e–h that after the limestone is placed for one month, its cracks develop more obviously. Sample 9 has a fracture extending to the edge of the rock surface. Sample 10 has two fine cracks extending outward. Sample 11 has three cracks expanding to the edges and the cracks become curved. Sample 12 has four cracks running through the surface of the rock and the degree of curvature of the cracks has increased significantly. The later crack development of the soaked sample is significantly better than that of the dried sample, indicating that the soaked samples have advantages in the later-stage crack growth after laser irradiation.

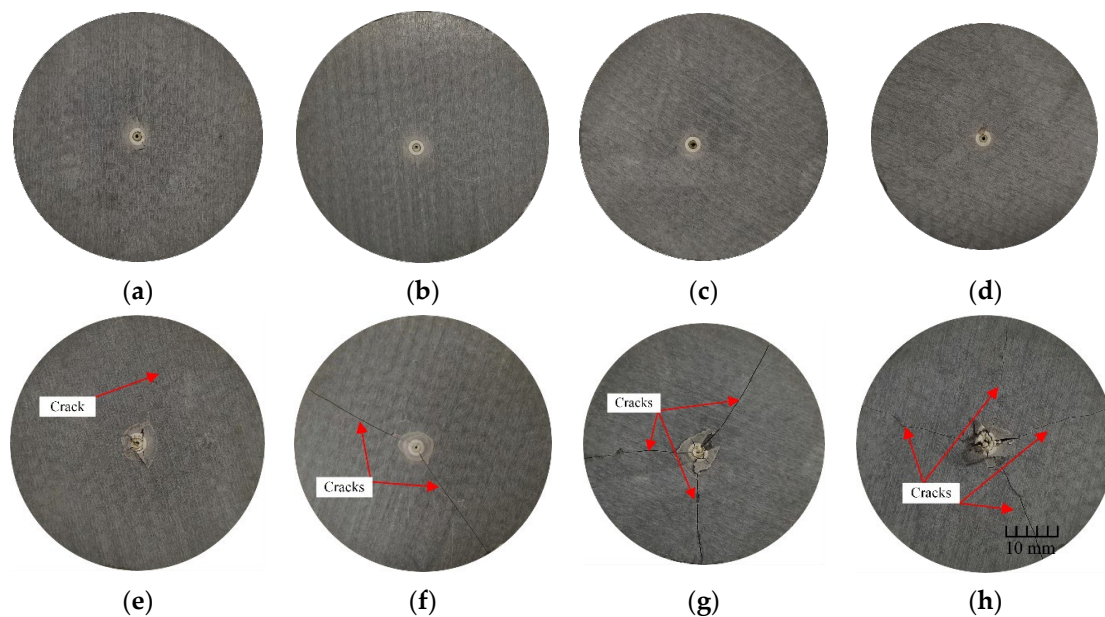


Figure 10. Surface morphology of soaked sample after laser irradiation at a power of 90 W: (a) 90 s; (b) 120 s; (c) 150 s; (d) 180 s; (e) 90 s after one month; (f) 120 s after one month; (g) 150 s after one month; and (h) 180 s after one month.

Figure 11 shows the images of the surface of the dried sample after irradiation with the power of 135 W for 90 s, 120 s, 150 s, and 180 s (corresponding rock numbers are #5, #6, #7, and #8 respectively). It can be seen from Figure 11e–h that after the limestone is placed for one month, its cracks develop more obviously. Sample 5 has three fine cracks extending outward. Sample 6 has three cracks radiating outward to the edge of the rock surface, one of which is wider. Sample 7 has three cracks extending to the edge of the rock, and a connecting crack connecting two of them. Sample 8 has four cracks extending to the edge of the rock. The cracks on the surface of the samples all develop greatly, resulting in part of the rock samples on the surface detaching or even cracking as a whole, and new cracks appear in some samples.

Figure 12 shows the images of the surface of the soaked sample after irradiation with the power of 135 W for 90 s, 120 s, 150 s, and 180 s (corresponding rock numbers are #13, #14, #15, and #16 respectively). It can be seen from Figure 12e–h that after the limestone is placed for one month, its cracks develop more obviously. Sample 13 has four fine cracks extending outward. Sample 14 has four cracks radiating outwards to the edge of the rock surface. Sample 15 has four cracks extending to the edge of the rock and a connecting crack connecting two of them. Sample 16 has four cracks extending to the edge of the rock, and one of the cracks has a branch crack, which increases the complexity of the cracks on the rock surface. In addition, it can be found that the crack opening increases with the increase of irradiation time. This is because the limestone composition is dense, and it is difficult to form cracks when the shape is complete. However, once the laser power and irradiation

time increase, cracks are generated and the integrity is destroyed, which would lead to the rapid development and growth of cracks. Eventually, part of the rock sample was peeled off from the surface of the sample.

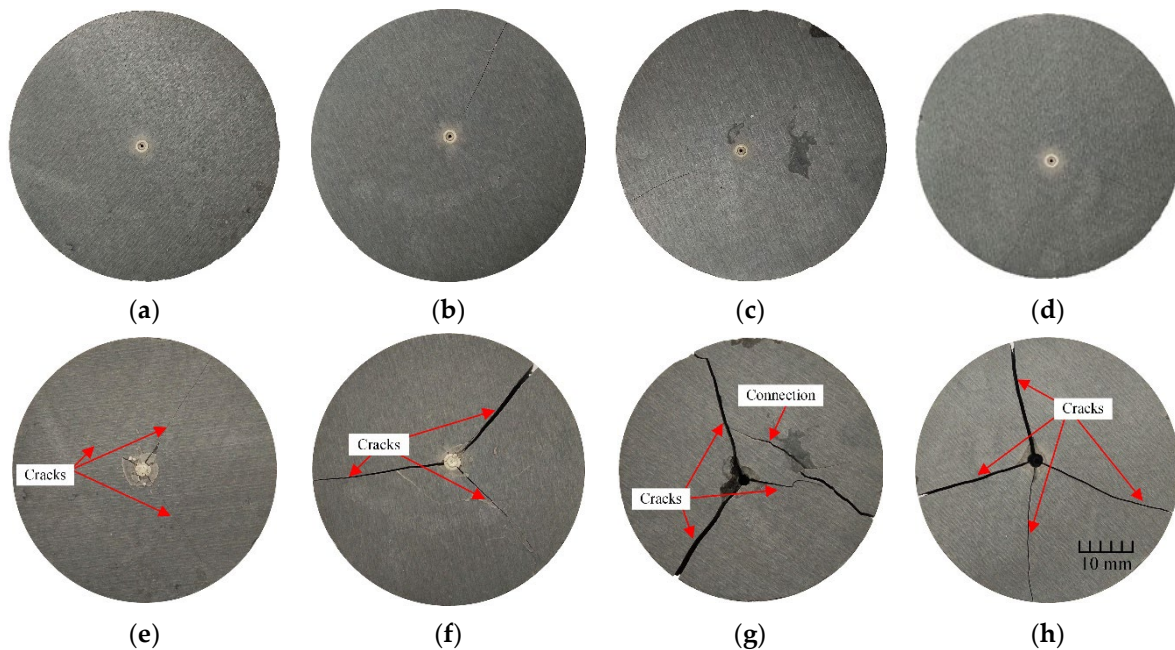


Figure 11. Surface morphology of dried sample after laser irradiation at a power of 135 W: (a) 90 s; (b) 120 s; (c) 150 s; (d) 180 s; (e) 90 s after one month; (f) 120 s after one month; (g) 150 s after one month; and (h) 180 s after one month.

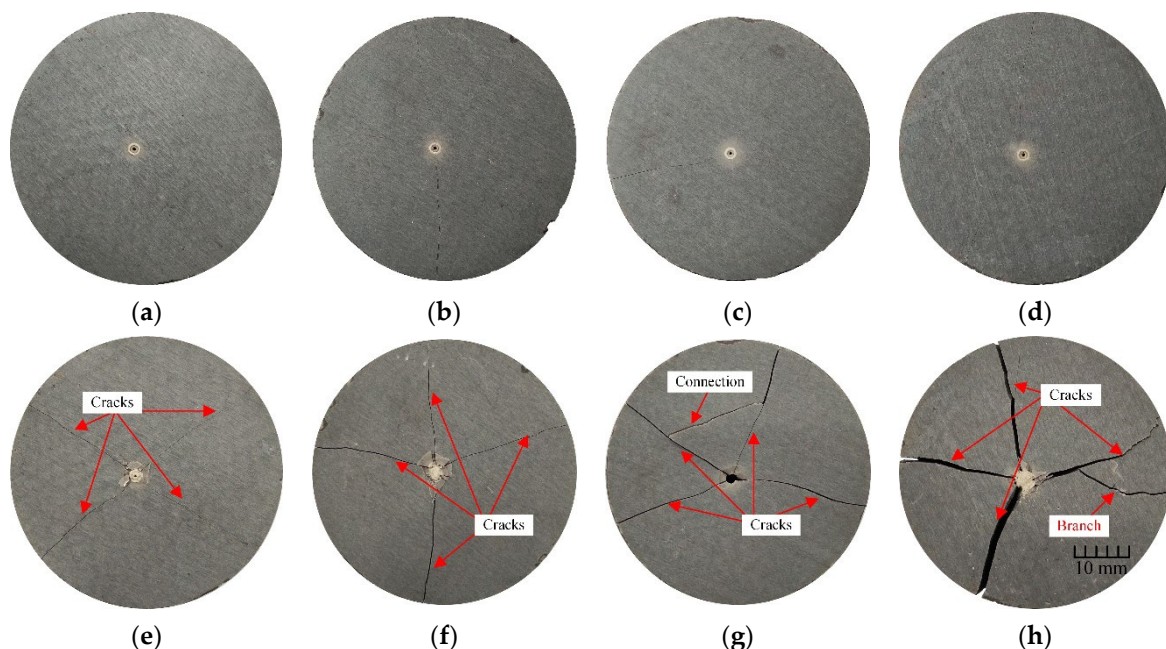


Figure 12. Surface morphology of soaked sample after laser irradiation at a power of 135 W: (a) 90 s; (b) 120 s; (c) 150 s; (d) 180 s; (e) 90 s after one month; (f) 120 s after one month; (g) 150 s after one month; and (h) 180 s after one month.

From the observation of Figures 9–12, it can be found that the cracks on the surface of the rock samples have developed considerably after being placed for one month. This is because the local high temperature caused by the laser irradiation causes the uneven

heating of the rock to generate deep cracks. In addition, the composition of limestone is dense, hard, and brittle. After the sample cools and shrinks, it is difficult for the cracks to be filled with cementitious substances, resulting in the continuous increase of the spacing and the gradual extension of the rock under the influence of its gravity. The melt in the vicinity of the borehole can also block the borehole after a long period of reaction, exerting lateral pressure on the rock sample which has gradually separated on both sides. At the same time, the molten material in the vicinity of the small holes turns into a white powder. The white substance is a calcium carbonate that is formed by reacting with moisture in the air for a long time to form calcium hydroxide, which then absorbs carbon dioxide and regenerates calcium carbonate. As a result of regeneration, the composition is loose, and the volume expands, blocking the original orifice to the point of overflowing the surface.

3.5. Variation of Fracture Length

Figure 13a depicts the trend in limestone fracture length for a laser power of 90 W. The fracture length of the dried samples after laser irradiation increases from 0.61 to 5.09 mm. The fracture length of the soaked samples after laser irradiation increases from 2.24 to 8.7 mm. Figure 13b depicts the trend in limestone fracture length for a laser power of 135 W. Fracture length increases from 6.30 to 9.85 mm for dried samples and from 9.04 to 11.38 mm for soaked samples. It can be seen that when the power is the same, the fracture length of the soaked specimen is greater than that of the dried specimen, and the longer the irradiation time, the crack length gradually increases. When the specimens are all dried, the higher the irradiation power, the more the fracture length gradually increased; when the specimens are all soaked, the higher the irradiation power, the more the fracture length gradually increased. This indicates that increasing the irradiation power and irradiation time is beneficial to the development of fractures and that the soaked specimens are equally beneficial to the later development of limestone fractures.

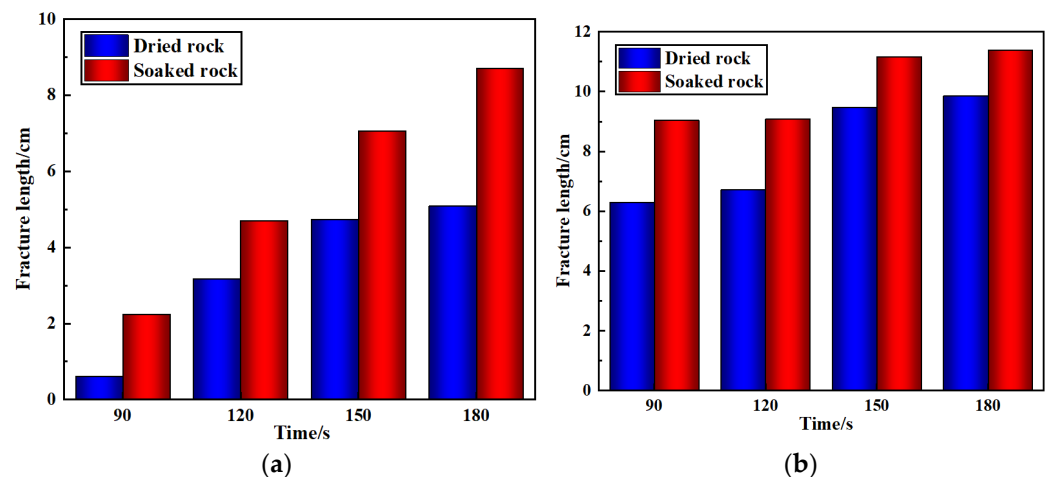


Figure 13. Fracture lengths of dried sample and soaked sample at different laser powers: (a) 90 W; and (b) 135 W.

4. Discussion

Thermogravimetric analysis is a technique to measure the relationship between mass and temperature under the condition of programmed temperature control. Thermogravimetric analyzer is mainly composed of a furnace, program temperature control system, and recording system. By analyzing the thermogravimetric curve, we can know the composition, thermal stability, thermal decomposition of the sample and its possible intermediate products, and other information related to the mass. Figure 14a shows the thermogravimetric curve obtained from the experiment. It can be seen from the curve that the soaked sample begins to show differences at 100 °C, which is caused by the evaporation of some free water molecules in the rock.

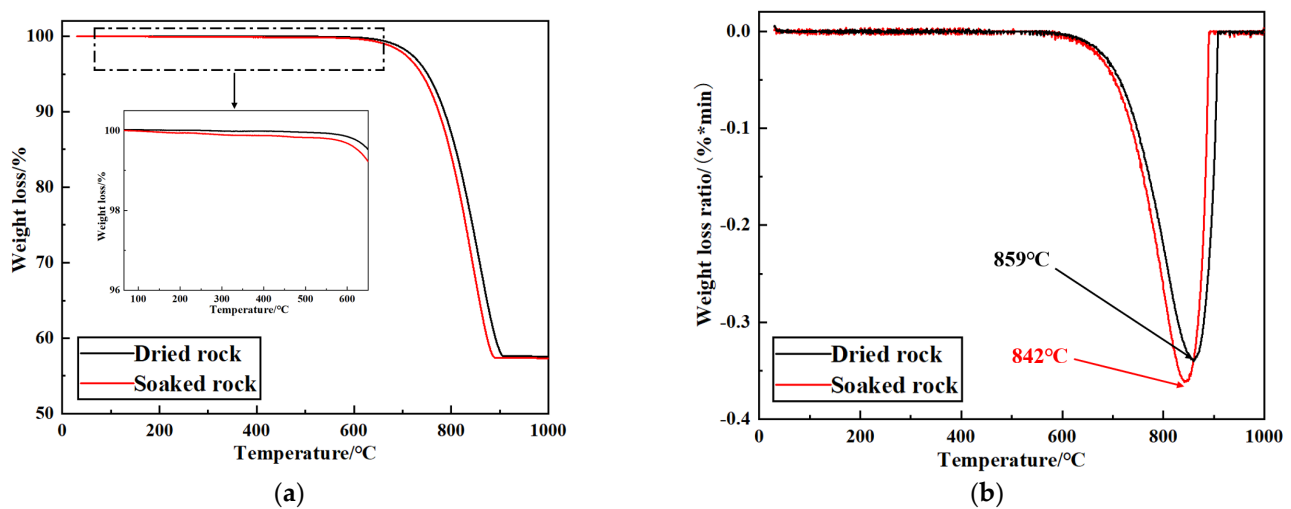


Figure 14. Plots of: (a) thermogravimetric curve; and (b) weight-loss rate with temperature.

Figure 14b shows the variation in percentage weight loss concerning temperature. It was observed that the weight loss of the soaked samples first drops and reaches a point of inflection at 842 °C. At the same temperature, the weight loss of the dried sample is always smaller than that of the soaked sample, reaching the inflection point at 859 °C and reaching equilibrium later than that of the soaked sample. This is because the soaked rock contains more free water inside. In addition, after the rock is soaked, the bound water inside the mineral component will also increase, so the temperature at the inflection point is lower than that of the dry sample, and the minerals inside will first complete decomposition to reach the equilibrium position.

5. Conclusions

In this study, the effects of immersion conditions on rock-breaking by laser irradiation on the temperature, hole size, rock-breaking efficiency, macro-fracture after laser irradiation, and fracture length were investigated. In addition, the changes in rock weight loss with temperature were determined using a thermogravimetric analyzer. The main conclusions can be drawn:

- (1) The temperature area over 100 °C increases with the increase of irradiation time and the one between 2.27 cm² and 13.20 cm² varies with the change of laser power between 90 W and 135 W. The specimen has a larger MSE and a smaller ROP at a power of 90 W compared with the 135 W, indicating that increasing the laser power improves the efficiency of rock-breaking. With the increase of the irradiation time, the MSE gradually increases, while the ROP gradually decreases;
- (2) The cracks on the surface of the rock samples developed considerably after being placed for one month. This is because the composition of limestone is dense, hard, and brittle. After the sample cools and shrinks, it is difficult for the cracks to be filled with cementitious substances, resulting in the continuous increase of the spacing and the gradual extension of the rock under the influence of its gravity;
- (3) The fracture length of the dried sample increased from 0.61 to 5.09 mm, and that of the soaked sample increased from 2.24 to 8.7 mm under a laser power of 90 W. The fracture length of the dried sample increased from 6.30 to 9.85 mm, and that of the soaked sample increased from 9.04 to 11.38 mm under a laser power of 135 W;
- (4) The soaked sample began to show differences when heated at 100 °C, which was caused by the evaporation of some free water molecules in the rock. The main weight-loss temperatures of the samples occur in the range of 640 °C to 900 °C. This is because dolomite and calcite are thermally decomposed during the high temperature area. Inflection-point temperatures for the weight-loss ratio of soaked and dried samples were 842 °C and 859 °C, respectively.

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