Optimization of Laser Irradiation Rock Process Parameters Based on Response Surface Methodology

Jie Li [1, a], Zhuyu Gao [1, b], He Bu [1, c], Bodan Kang [1, d], Jingbo Guo [1, e], and Yuanjun Huang [1, f]

[1] School of mechanical engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China.

[a] tbmlijie@126.com, [b] gaozyyx2023@163.com, [c] buhe@student.stdu.edu.cn,

[d]1311709543@qq.com, [e] guojingbo66@163.com, [f] h763814261@qq.com

Abstract. Aiming at the problem that mechanical rock-breaking is difficult when facing complete high-strength surrounding rock, laser irradiation rock can weaken the strength of rock and effectively improve the rock breaking efficiency. In this paper, the optimization of laser irradiation rock process parameters was carried out. The laser irradiation rock test was conducted using the laser irradiation rock test platform under the conditions of different laser power, spot movement speed and spot diameter. The prediction model of the rock uniaxial compression strength was established based on the response surface methodology, and the mapping relationship between laser process parameters and the rock uniaxial compression strength was explored. With the minimization of the rock uniaxial compression strength as the optimization objective, the laser process parameters were optimized, and the feasibility of the optimization method was verified by experiments. The results showed that the minimum rock uniaxial compression strength obtained from the optimized process parameters decreased by 30.32% compared to the initial rock uniaxial compression strength. The prediction model constructed in this paper has good stability, strong generalization ability and prediction accuracy for the prediction of the rock uniaxial compression strength. The results of the study provide a scientific basis and engineering guidance for the selection of laser parameters in laser rock-breaking technology.

Keywords: Laser rock breaking; Laser process parameters; Response surface methodology; Parameter optimization.

1. Introduction

Laser rock breaking is characterized by non-contact interaction, high energy density, low energy consumption, and high efficiency. These advantages render it highly promising for applications in oil and gas drilling, as well as tunnel boring [1, 2, 3]. The technology irradiates the rock with lasers, causing melting and vaporization on the surface of rock, creating micro-cracks inside rock through thermal stresses [4]. The efficiency and effectiveness of rock breaking are affected by factors such as laser parameters, rock characteristics and laser transmission medium [5, 6]. Adjusting the laser parameters can change the area of thermal action and the amount of heat absorbed by the rock, thus improving the crushing efficiency. Therefore, optimization of laser parameters is the key to improving the efficiency and effectiveness of laser rock breaking.

In order to elucidate the influence of laser parameters on rocks and to improve the rock breaking effect of lasers, many scholars have carried out a lot of research work: Among them, Wang et al. [7] explored the effects of laser power, distance and irradiation time on rock strength, rock composition, and cracks. They found that the rock compressive strength could be decreased by 69% at most after laser irradiation. Shahin Jamali et al. [8] conducted laser-rock softening tests with different laser parameters and rock types. The effect of laser parameters on rock softening was explored. Xu et al. [9] studied the effect of laser power and irradiation time on the weakening of rock strength. They found that craters and cracks were the main reasons for the decrease of rock compressive strength. Fu et al. [10] investigated the temperature, melt cratering and yield condition of rock under continuous and pulsed laser action by experiment and finite element methods. The study provided suggestions for the selection of lasers in the rock breaking process.

Previous studies have mainly focused on vertical laser hole formation, while the effect of moving laser process parameters on rock has not been explored in depth. In this paper, laser power, spot movement speed, and spot diameter are selected as the parameters to be investigated for laser irradiation of rocks. The uniaxial compressive strength prediction model is established using the response surface methodology. The laser process parameters are optimized based on this model. Finally, the predictive performance of the model is experimentally validated. This study realizes the optimization of the laser process parameters and provides a scientific basis and technical support for the selection of laser parameters in practical engineering applications.

2. Test Equipment and Scheme Design

2.1 Test Equipment and Sample Preparation

In this paper, the laser irradiation rock test platform (Fig. 1) was used, including a laser head, laser transmitter, laser control system, water-cooling system, conveyor, and so on. The laser was controlled by the laser control system to precisely emit laser beams with different parameters. Rock specimens were moved horizontally using the conveyor.

The specimen material was granite and the initial uniaxial compressive strength was 113 MPa. After the laser irradiation rock test, the uniaxial compressive strength of the specimens was measured using the universal testing machine.

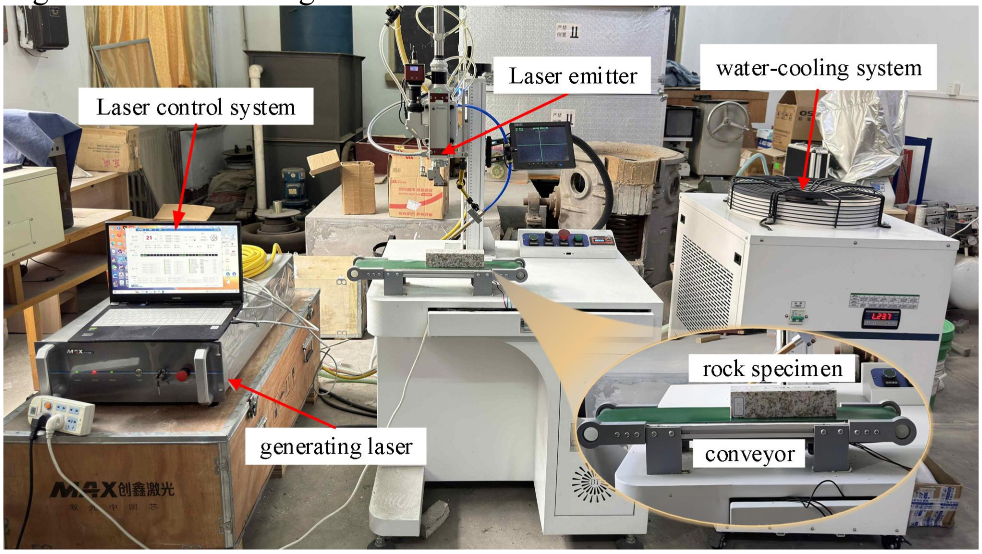


Fig. 1 The laser irradiation rock test platform

2.2 Design of Test Scheme Based on Rresponse Surface Methodology

This study employed the Box-Behnken Design (BBD) method to develop an experimental matrix comprising three factors at three distinct levels (Table 1). The selected independent variables encompassed laser power, spot movement speed, and spot diameter. The rock uniaxial compression strength served as the output metric.

The laser irradiation rock test was carried out. The uniaxial compressive strength of these tested specimens was recorded and summarized. The test results are shown in Table 2.

Table 1. Test process parameters and range

Factors	Levels		
	-1	0	1
P_b / W	1800	2000	2200
V / mm/s	10	13.5	17
R_b / mm	14	16	18

Table 2. Statistics of test parameters and response values

No.	Process parameters			σ_c (Mpa)
	P_b (W)	V (mm/s)	R_b (mm)	
1	1 800	10	16	87.43
2	2 200	10	16	80.39
3	1 800	17	16	94.74
4	2 200	17	16	85.25
5	1 800	13.5	14	86.11
6	2 200	13.5	14	82.11
7	1 800	13.5	18	88.19
8	2 200	13.5	18	80.12
9	2 000	10	14	82.21
10	2 000	17	14	87.14
11	2 000	10	18	82.32
12	2 000	17	18	84.36
13	2 000	13.5	16	79.64
14	2 000	13.5	16	79.31
15	2 000	13.5	16	80.56
16	2 000	13.5	16	79.20
17	2 000	13.5	16	78.96

3. Establishment and Analysis of the Rock Uniaxial Compressive Strength Prediction Model

3.1 Establishment of Prediction Model

According to the test data in Table 2, the RSM prediction model was established with the rock uniaxial compression strength as the response value. The model was analyzed by ANOVA [12], and the results are shown in Table 3.

Table 3. ANOVA table of the rock uniaxial compression strength

Source	Sum of Squares	Freedom	Mean Square value	F	P
Model	285.43	9	31.71	26.51	0.0001
P_b	102.25	1	102.25	85.47	< 0.0001
V	45.79	1	45.79	38.28	0.0005
R_b	0.832	1	0.832	0.695	0.4318
P_bV	1.5	1	1.5	1.25	0.2997
P_bR_b	4.14	1	4.14	3.46	0.1051
VR_b	2.09	1	2.09	1.75	0.228
P_b^2	59.9	1	59.9	50.07	0.0002
V^2	55.99	1	55.99	46.81	0.0002
R_b^2	2.88	1	2.88	2.41	0.1648
Lack of fit	6.82	3	2.27	5.85	0.0605
R^2	0.9715	C.V. %		1.31%	
$R2_{Adjusted}$	0.9349	Adeq Precision		17.06	

As shown in Table 3, the P-value is an indicator of the model reliability. The P-value of the RSM prediction model is 0.0001 < 0.05 and the P-value of the lack of fit is 0.060 > 0.05, this indicates that the constructed model is significant and the lack of fit is not significant. The correlation coefficient $R^2 = 0.9610$, Adeq Precision 17.06 > 4, and coefficient of variation C.V. = 1.31% < 10%; all of the model test values indicate that the RSM prediction model accurately describes the link between the laser process parameters and the rock uniaxial compression strength. The F-value is used to characterize the significance of the relationship between each process parameter in the model and the response value. By comparing the F-value of each process parameter, the primary and secondary order of influence on the rock uniaxial compression strength can be obtained: laser power > spot movement speed > spot diameter.

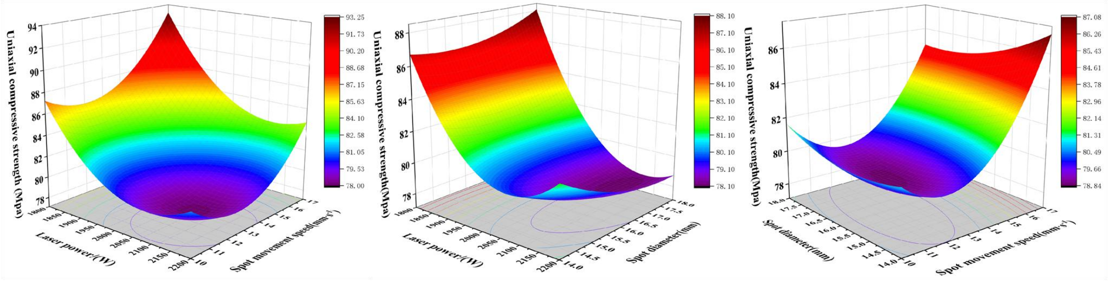
According to the second-order regression model fitted to the test data, the regression equation for the rock uniaxial compression strength is obtained as:

$$\begin{aligned} F(x) = \sigma_c = 457.16809 - 0.337737*P_b - 3.84694*V + 0.089643*R_b \\ -0.000875*P_bV - 0.002544*P_bR_b - 0.103214*VR_b \\ +0.000093*{P_b}^2 + 0.293776*V^2 + 0.194688*{R_b}^2 \end{aligned} \tag{1}$$

3.2 Interactive Analysis of Process Parameters

Based on the RSM prediction model of the rock uniaxial compression strength, three-dimensional charts (Fig. 2) were drawn to show the interaction of the process parameters. Figure 2 visualizes the effect of laser power, spot movement speed, and spot diameter on the rock uniaxial compression strength under their interaction.

From Fig. 2(a), it can be seen that the increase in laser power and the decrease in spot movement speed lead to the increase of laser energy density and the prolongation of irradiation time. When the laser power is in the range of 1950 to 21 n50 W and the spot movement speed is in the range of 11 to 14 mm/s, the rock uniaxial compression strength decreases; beyond these ranges, the rock uniaxial compression strength increases. The coupling effect of laser power and spot movement speed can be effectively exerted within the appropriate parameter range. According to Fig. 2(b), the rock uniaxial compression strength is lower at larger laser power and larger spot diameter. When the laser power is constant, the change in spot diameter has no significant effect on the rock uniaxial compression strength. From Fig. 2(c), it can be seen that the decreasing slope of spot movement speed is steeper than that of spot diameter. This indicates that the spot movement speed has a greater effect on rock uniaxial compression strength. The analytical result is consistent with the F-value analysis in Table 3. The overall trend of rock uniaxial compression strength increases with decreasing spot movement speed.



(a) (b) (c)

Fig. 2 Interaction effect of laser process parameters on rock uniaxial compression strength
(a) P_bV (b) P_bR_b (c) VR_b

Therefore, in order to obtain a smaller rock uniaxial compression strength, a larger laser power and a smaller spot movement speed are selected in these parameter ranges.

4. Optimization of Laser Process Parameters and Experimental Verification

4.1 Optimized Design Models for Process Parameters

In order to find the optimal solution for the objective function when the constraints are satisfied, an optimized design model is established. The model mainly includes objective function, design variables, and constraint conditions [11].

The purpose of the optimized design model in this paper was to optimize the laser irradiation rock process parameters. The optimization object was the minimum rock uniaxial compression strength, and the objective function was the regression equation of rock uniaxial compression strength. The design variables of this model were laser power, spot movement speed, and spot diameter. The model constrained the range of laser process parameters, where the ranges of laser power, spot movement speed, and spot diameter were 1800 W to 2200 W, 10 mm/s to 17 mm/s, and 14 mm to 18 mm, respectively.

The optimized design model for the laser irradiation rock process parameters is as follows:

$$\begin{cases} (\sigma_c)_{\min} = \min[F(x)] \\ X = [x_1, x_2, x_3] = [P_b, V, R_b] \\ 1800 \leqslant x_1 \leqslant 2200, 10 \leqslant x_2 \leqslant 17, 14 \leqslant x_3 \leqslant 18 \end{cases} \tag{2}$$

Based on this model, the optimal process parameters were obtained using the response surface methodology: laser power was 2107.273 W, spot movement speed was 13.362 mm/s, and spot diameter was 17.695 mm, and the optimized minimum rock uniaxial compression strength was 78.50 MPa.

4.2 Experimental Verification

The laser irradiation rock test was carried out using the optimized process parameters, and the test was repeated three times. The average value of rock uniaxial compression strength obtained from the tests was 78.74 MPa.

According to the test results in Table 4, it can be seen that the optimized minimum rock uniaxial compression strength decreases by 30.32% compared to the initial rock uniaxial compression strength. The relative error between the optimized rock uniaxial compression strength and the experimental values is 0.3%.

Table 4. Results of experimental validation

Model		P_b (W)	V (mm/s)	R_b (mm)	σ_c (MPa)
RSM	Optimized	2107.273	12.362	17.695	78.50
	Experiment	2107	12.4	17.7	78.74
	Relative Error	-0.13%	0.3%	0.028%	0.3%

5. Conclusions

This paper focused on the optimization problem of laser irradiation rock process parameters. Based on the laser irradiation rock test platform, using the Box-Behnken Design, the laser irradiation rock test was carried out, the RSM prediction model of the rock uniaxial compression strength was established, and the laser process parameters were optimized by the response surface methodology. The conclusions are as follows:

(1) The RSM prediction model of the rock uniaxial compression strength was developed. The relationship between laser process parameters and the rock uniaxial compression strength was explored. The results showed that the laser power had the greatest effect on the rock uniaxial compression strength, followed by spot movement speed, and spot diameter had the least effect.

Within the studied parameter range, increasing the laser power and decreasing the spot movement speed reduced the rock uniaxial compression strength.

(2) Taking the minimum rock uniaxial compression strength as the optimization objective, the laser process parameters were optimized using the response surface methodology, and the accuracy of the optimization results was verified by experiments. The optimized rock uniaxial compression strength was reduced by 30.32% compared to the initial rock uniaxial compression strength. This result meant that the RSM prediction model has good stability, wide adaptability and accurate prediction ability in predicting the rock uniaxial compression strength.

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