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Numerical simulation and experimental investigation on fracture mechanism of granite by laser irradiation

Meiyan Li [a,*], Bin Han [a], Shiyi Zhang [a], Lixin Song [b], Qingkun He [c]

[a] College of Mechanical and Electronic Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China
[b] Offshore Oil Engineering (Qingdao) Co., Ltd., Qingdao 266520, China
[c] Experiment Center of College of Materials Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

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ABSTRACT

Numerical simulation and experimental tests are conducted to determine the stress distribution and fragment mechanism of granite during laser perforation. The mechanisms of material removal through laser perforation are spallation, melting and ablation. High intensity laser energy concentrates locally on the granite surface area and causes the local temperature to increase instantaneously. The closer the center of laser beam is, the higher the temperature is. With the laser power increasing the size of laser perforation hole is expanded. In addition, the high heating and cooling rates induced by laser irradiation brings out the generation of high tensile stress (481–536 MPa), which is far higher than the tensile strength (11 MPa) of granite sample, and fracture or spallation occurs. Fracture analysis showed the inner wall of the glassy layer after laser perforation is smooth with lots of pores. Moreover, there is a hackle region with regular strips of micron/nano scale at the edge to the glassy layer, and the secondary cracks propagate perpendicular to the regular strips. Compared with the fracture morphology of the glassy layer, the fracture surface of the interfacial transition zone is coarse, and obvious secondary cracks also generate. Obviously, the fracture mechanism of granite faced to laser irradiation is the typical brittle fracture.

1. Introduction

The current method of mechanical drilling has been in wide use since the early part of the twentieth century. Subsequent improvements have been incremental, limited by the physics of the cutting method. Especially drilling for hard rocks is particularly challenging because of the requirement of an extremely robust drill bit and rugged Bottom Hole Assembly (BHA) in order to penetrate the rocks [1]. Due to the unique properties such as high intensity and low divergence, lasers have been widely used in a wide range of industrial application [2–4]. In recent years, many researches demonstrated the feasibility of laser/rock destruction using high intensity laser on different rock types [5–7]. Early studies from the 1960s and 1970s about laser energy applications for well construction are primarily theoretical, with the assumptions that rock removal mechanisms were due to the melting of rocks. Since 1997, initial investigations involving high power lasers were performed to determine the possible applications in drilling and completing oil and gas wells [8]. Subsequently, a considerable number of researches on laser perforation have been conducted with the varying processing parameters. Ahmadi et al. [9] determined the effect of confining pressure on specific energy in Nd: YAG laser perforating of rock. Ohtani et al. [10] irradiated a rock surface submerged below water with pulsed Ho: YAG laser beam and found that the rock surface became molten before its proper penetration.

In addition, some other researches worked on many projects about laser and rock interaction [11] or using laser setups to drill the oil and gas well [12]. Three mechanisms contribute in laser perforation: spallation, melting and evaporation [13,14], which are induced by momentary temperature growth in rock. Especially, vaporization usually can be caused at long irradiation of high power lasers on the surface melted rocks. As we know, the stress states induced by laser are the main factor of rock fracture. However, few studies are conducted on the stress field distribution of rocks by laser irradiation.

This paper reports the simulated and experimental results of laser perforation applied high power laser. Simulation is focused on the investigation of thermal and stress distributions involved in laser perforation in granite samples. Combined with the SEM morphologies of fracture surface, the physical processes occurring during laser irradiating on the surface of granite samples are given.

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[*] Corresponding author at: College of Mechanical and Electronic Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China.
E-mail address: limeiyan@upc.edu.cn (M. Li).

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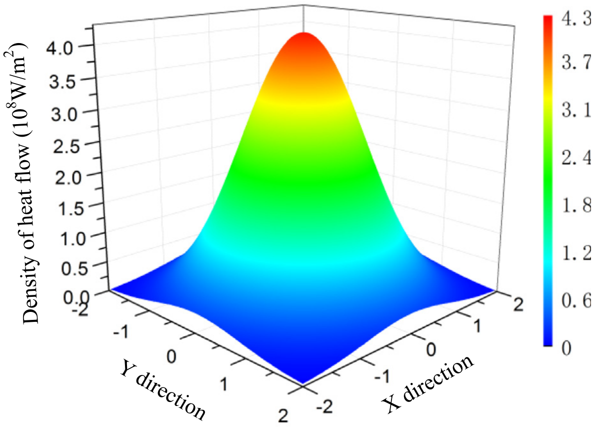

Fig. 1. The spatial distribution maps of laser energy (Q = 1000 W, R_b = 1.5 mm).

2. Finite element modeling

2.1. Heat source model

In this paper, finite element software ANSYS was applied to simulate the laser irradiation process. The laser irradiation is considered as a volumetric heat source to be absorbed in a volume of a green body. A Gaussian distribution of the heat flux density is defined by the following equation [15]:

$$I(r) = I_0 exp\left(\frac{-kr^2}{R_b^2}\right) \tag{1}$$

where r is the distance from the center of laser beam; R_b is the radius of laser beam; k is power concentration factor; I_0 is the laser intensity.

The initial temperature of granite sample was 20 °C. Assumedly, when the value of *k is* 3, laser power is 1000 W, and the radius of laser beam is 1.5 mm, the maximum heat flux density could reach $4.3 \times 10^8 \mathrm{W/m^2}$. The spatial distribution map of laser energy is shown in Fig. 1, and x and y direction are used to characterize the 2-D dimension of the distribution of heat flux density. It can be seen that the distribution of heat flux density is symmetrical along x and y direction.

The equation of heat conduction during laser irradiating on the surface of granite is expressed by:

$$\rho c_p \frac{\partial T}{\partial t} - \lambda_t \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right] = 0 \tag{2}$$

where T is the temperature of granite, ρ is the density of granite, λ_t is the heat conductivity coefficient of granite sample, and C_p is constant-pressure specific heat.

The initial and boundary conditions of the equation of heat conduction are expressed as follows [15]:

$$T|_{t=0} = T_0 \tag{3}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = \frac{\partial T}{\partial r}|_{r=\frac{b}{2}} = 0 \tag{4}$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0, \ \frac{\partial T}{\partial z}|_{z=h} = I(r) \tag{5}$$

where T is the temperature of granite, b is the radius of the granite sample.

2.2. Physical model

The mathematical analysis method is difficult to solve the engineering problem of laser irradiating, so the finite element simulation software ANSYS usually is applied to analyze the temperature and stress fields. The 3-D model is necessary to simulate the heat transfer and thermal stress, and analyze the breaking mechanism of rocks by laser irradiation. The size of model of cylindrical rock sample is Φ25 mm × 50 mm.

Due to the symmetry of the rock model and the heat source, for the convenience of calculation and displaying the results, a quarter symmetry model of the cylinder is chosen. The physical model is exhibit in Fig. 2. Mixed gridding technology is applied and the gridding of the center region is minished, as shown in Fig. 2b–d.

Table 1
Heat physics parameters and mechanical parameters of granite [9,13].

Parameters	Units	Granite
Density	g/cm^3	2.7–2.9
Specific heat capacity	J/(g K)	0.8
Heat conductivity	W/(M K)	2.6–3.35
Line expand coefficient	K^{-1}	8.3×10^{-6}
Poisson' ratio	–	0.3
Vaporization temperature	°C	2230
Compressive strength	MPa	199.95
Tensile strength	MPa	11.06

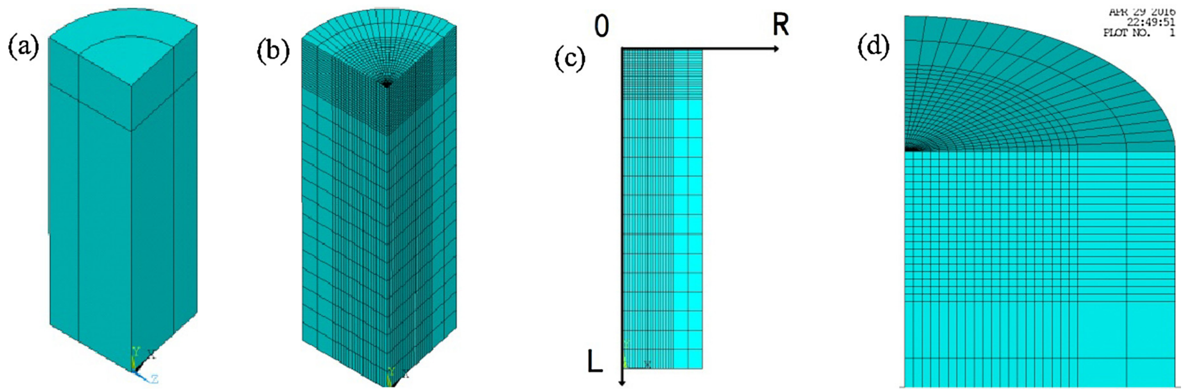

Fig. 2. Three dimensional models and meshing of granite sample. (a) 3-D model; (2) meshing; (c) 2-D meshing model; (d) partial detail at high magnification.