Specific energy for pulsed laser rock drilling

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Application of advanced high power laser technology to oil and gas well drilling has been attracting significant research interests recently among research institutes, petroleum industries, and universities. Potential laser or laser-aided oil and gas well drilling has many advantages over the conventional rotary drilling, such as high penetration rate, reduction or elimination of tripping, casing, and bit costs, and enhanced well control, perforating and side-tracking capabilities. The energy required to remove a unit volume of rock, namely the specific energy (SE), is a critical rock property data that can be used to determine both the technical and economic feasibility of laser oil and gas well drilling. When a high power laser beam is applied on a rock, it can remove the rock by thermal spallation, melting, or vaporization depending on the applied laser energy and the way the energy is applied. The most efficient rock removal mechanism would be the one that requires the minimum energy to remove a unit volume of rock. Samples of sandstone, shale, and limestone were prepared for laser beam interaction with a 1.6 kW pulsed Nd:yttrium–aluminum–garnet laser beam to determine how the beam size, power, repetition rate, pulse width, exposure time and energy can affect the amount of energy transferred to the rock for the purposes of spallation, melting, and vaporization. The purpose of the laser rock interaction experiment was to determine the optimal parameters required to remove a maximum rock volume from the samples while minimizing energy input. Absorption of radiant energy from the laser beam gives rise to the thermal energy transfer required for the destruction and removal of the rock matrix. Results from the tests indicate that each rock type has a set of optimal laser parameters to minimize specific energy (SE) values as observed in a set of linear track and spot tests. As absorbed energy outpaces heat diffusion by the rock matrix, local temperatures can rise to the melting points of the minerals and quickly increase observed SE values. Tests also clearly identified the spallation and melting zones for shale samples while changing the laser power. The lowest SE values are obtained in the spalling zone just prior to the onset of mineral melt. The laser thermally spalled and saw mechanically cut rocks show similarity of surface microstructure. The study also found that increasing beam repetition rate within the same material removal mechanism would increase the material removal rate, which is believed due to an increase of maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

Key words: pulsed laser, rock drilling, specific energy, thermal spallation

I. INTRODUCTION

Since the turn of the 20th century, rotary drilling has been a dominant technique for well production in the oil and gas industry. According to a Gas Technology Institute study conducted in 1995, 50% of the well production time is spent on making hole, 25% of the time on tripping, and 25% of the time on casing/cementing. In 1999, approximately 20 000 wells, with an average depth of 6000 ft, were drilled onshore in the United States.[1] The total estimated cost, at rate of $128/ft, was 15.36 billion. Major reduction in drilling costs can be obtained by drilling faster and reducing requirements for drill string removal, bit replacement and setting casing.

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TABLE I. Rock sample compositions and thermal properties.

Rock type	Compositions	%	Bulk density (g/cm^3)	Thermal conductivity × 10^3 (J/cm s K)	Specific heat capacity (J/g K)	Diffusivity (cm^2/s)
Berea Gray	SiO_2	85	2.15	25.9	0.88	13.6
	Al_2O_3	10				
	Fe	3				
	Rest	2				
Shale	SiO_2	35	2.36	—	—	7.5
	Al_2O_3	20				
	Fragment/clays	45				

Tremendous advances in high power laser technologies in recent decades showed the potential that laser could just do that. In fact, the initial laser drilling experiments on reservoir rocks conducted with the U.S. Army's Mid-Infrared Advanced Chemical Laser (MIRACLE) and the U.S. Air Force's Chemical Oxygen-Iodine Laser (COIL) systems showed the potential of laser drilling.[2] Both systems operated in the infrared optical region with power delivery capacities of 1 MW and 10 kW, respectively. The penetration rate by the systems was reported 100 times faster than current conventional drilling rates. Also, the experiments indicated that at such high powers there were deleterious secondary effects that increased as the hole depth increased. These effects included the melting and remelting of broken material, exsolving gas in the lased hole, and induced fractures, all of which reduced the energy transfer to the rock and therefore the penetration rate. More basic researche needs to be done in a systematic scientific approach to better understand laser–rock interaction.

When applying high power lasers on rocks, the laser can spall, melt, or vaporize the rock as the energy transferred to the rock raises its temperature locally. In order to break rock by mechanically or thermally induced stresses, sufficient power must be applied to the rock such that the induced stresses exceed the rock's strength. Similarly, when fusing rock, sufficient heat must be generated to produce local temperatures that exceed the melting temperature of the rock. Once these threshold values of power and energy are exceeded, the amount of energy required to break or remove a unit volume of rock remains nearly constant. This energy parameter, which is a measure of the efficiency of the rock destruction technique, is defined as specific energy (SE).[3] The term is commonly used by the drilling industry in discussions of the efficiency of mechanical drilling, particularly in measuring effectiveness of new bit designs, so that definition is familiar to the industry. SE is relationally defined as follows:

$$SE(J/cm^3) = \text{energy input/volume removed.} \quad (1)$$

The most efficient rock removal mechanism would be the one that requires the minimum SE value.

There are factors that affect the amount of absorbed energy transferred to the rock samples, known as secondary effects, and include the creation of melted materials, beam absorbing exsolved gases in the lased hole, and induced fractures in the surrounding rock. Obtaining the true specific energy of laser drilling was very difficult due to the secondary effects. In the current investigation, shallow holes (depth $<$ diameter) were produced by carefully controlling the laser beam irradiance and exposure time to avoid most of the secondary effects.

Samples of sandstone, shale, and limestone were prepared for laser beam interaction with a 1.6 kW pulsed Nd:yttrium–aluminum–garnet (YAG) laser beam to determine how the beam size, power, repetition rate, pulse width, exposure time, and energy can affect the amount of energy transferred to the rock for the purposes of spallation, melting and vaporization. The purpose of the laser–rock interaction experiment was to determine the optimal parameters required to remove a maximum rock volume from the samples while minimizing energy input. Only the SE results obtained on sandstone and shale are reported in this article. The results on limestone were reported elsewhere.[4] First, studies were carried out to investigate the correlation between the rock removal mechanisms and beam irradiance through a linear track method with simultaneous change of beam size on the rock surface. Then the test matrixes were carefully designed and performed based on the established correlation to quantitatively determine the nearly true specific energy. Absorption of radiant energy from the laser beam gives rise to the thermal energy transfer required for the destruction and removal of the rock matrix. Results from the tests indicate that the rates of heat diffusion in rocks are easily and quickly overrun by absorbed energy transfer rates from the laser beam to the rock. As absorbed energy outpaces heat diffusion

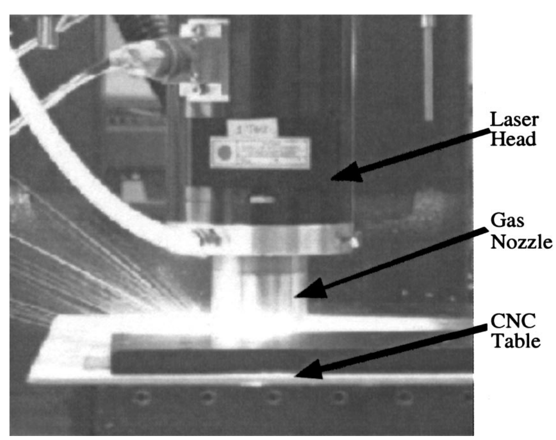

FIG. 1. Annotated photograph of the laser drilling system.

TABLE II. Laser parameters for Nd:YAG linear track tests.

Rock type	Calculated			Measured		
	Average power (W)	Peak power (W)	Energy per pulse (J/pulse)	Average power (W)	Peak power (W)	Energy per pulse (J/pulse)
Berea Gray	1600	4000	2	686	1715	0.86
	1600	4000	4	874	2185	2.18
	1600	8000	8	1156	5780	5.78
	1600	8000	16	1236	6180	12.36
	1600	16 000	32	1310	13 000	26.2
Shale	1600	8000	16	1156	5780	5.78

by the rock matrix, local temperatures can rise to the melting points of the minerals and quickly increase observed SE values. Tests also identified the spallation and melting zones for shale samples while changing the laser power. The lowest SE values are obtained in the spalling zone just prior to the onset of mineral melt. The study also found that increasing beam repetition rate within the same material removal mechanism zone would increase the material removal rate, which is believed due to an increase of maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

II. EXPERIMENTAL PROCEDURES

A. Test materials

The rocks used in this study were Berea Gray Sandstone and Frontier Shale with two different dimensions: 1.27 cm in thickness and 7.62 cm in diameter disks and $25\times5\times1.8$ cm slabs. Their composition and thermal properties are shown in Table I.[5]

B. Laser drilling system

The results reported here were conducted with a laser drilling system that consists of a 1.6 kW pulsed Nd:YAG laser with fiber–optic beam delivery, five-axis computer numerical control (CNC) workstation, and coaxial purging gas unit (Fig. 1). Fiber–optic beam delivery is particularly attractive because of its inherent flexibility and potential to deliver the high power beam down in the well.[6,7] A 12.5 cm transmissive focusing lens was used to defocus the beam to desired spot sizes. A constant nitrogen flow of 189 l/min (400 ft^3/h) was coaxially delivered to the rock by a drilling nozzle 6 cm in diameter.

C. Linear track tests

In order to identify each possible laser–rock interaction zone and the corresponding laser processing parameters, a group of linear tracks were produced by continuously moving the slab under a beam whose focal position with respect to rock surface was simultaneously changed from 0.5 mm to 20 cm by moving the focusing lens upward away from the slab. A wide range of laser parameters were tested (Table II). The ranges of parameters tested were energy per pulse from 2 to 32 J/pulse, repetition rate from 50 to 800 1/s, peak power from 4 to 16 kW, and pulse width from 0.5 to 2 ms. The calculated average power was fixed at 1600 W for each test, while the actual delivered (measured) powers were lower from 686 to 1310 W. The difference is mainly due to losses in the fiber optic delivery and the fact that at low energies/pulse (2 J/pulse) the laser does not output power as efficiently as at high energy per pulse.

D. Specific energy measurement

Based on the linear track results, test parameter matrixes around thermal spallation and slight melting zone, where the

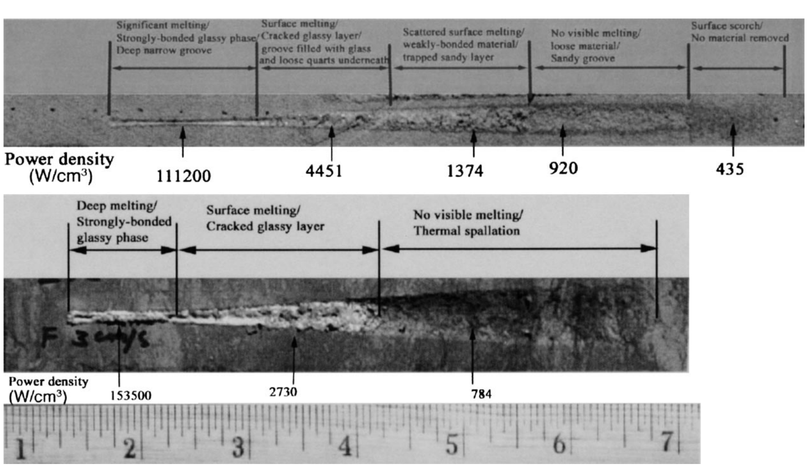

FIG. 2. Nd:YAG linear tracks with focal position change of Berea Gray sandstone (up) and shale (bottom) indicating the laser–rock interaction zones and corresponding beam irradiance.

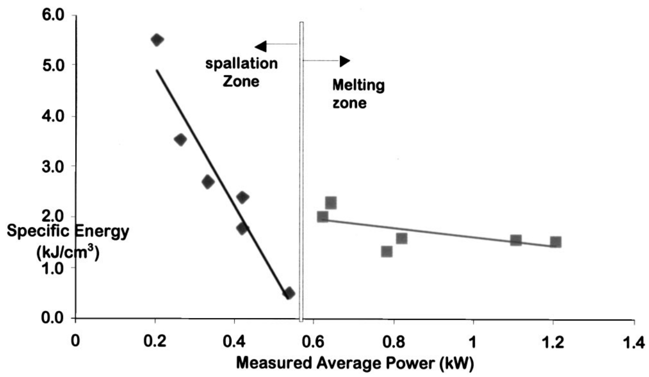

FIG. 3. Specific energy as a function of laser power for shale samples drilled at fixed beam size of 0.5 in. and exposure time of 0.5 s.

most potential minimum SE are, were selected and performed on disk rock samples. The matrixes included three energy per pulse levels: 4, 8, and 16 J/pulse, each with specific pulse width and repetition rate. The pulse width was either 1 or 2 ms, whereas the repetition rate varied between 50 and 400 pulse/s. The beam diameters on the rock surface were 1.27 and 0.95 cm. The beam exposure time was controlled at 0.5 and 1.0 s to only produce a shallow hole so that the secondary effects could be mostly avoided. To determine the material removed by the laser, the rock sample was precisely weighed pre- and postlasing using a Mettler AT 261 balance with maximum 205 g/62 g and resolution 0.1 mg/0.01 mg. The removed volume was then calculated based on the rock bulk density.

III. RESULTS AND DISCUSSION

A. Linear track tests

The resulting tracks are shown in Fig. 2. From left to right of the rock samples, different laser–rock interaction zones are identified by regions of similar physical reaction observed in the rock from intense melting to scorching. Also shown in the figure is the beam irradiance associated with each interaction zone, which decreased from left to right of the samples. For Berea Gray sandstone, five zones identified are Zone I: significant melting/strongly bonded glassy phase; Zone II: surface melting/cracked glassy layer; Zone III: scattered surface melting/weakly bonded material; Zone IV: no visible melting/material removed by thermal spallation; and Zone V: surface scorch/no material removed. For shale, because of shorter rock sample length received, laser radiation

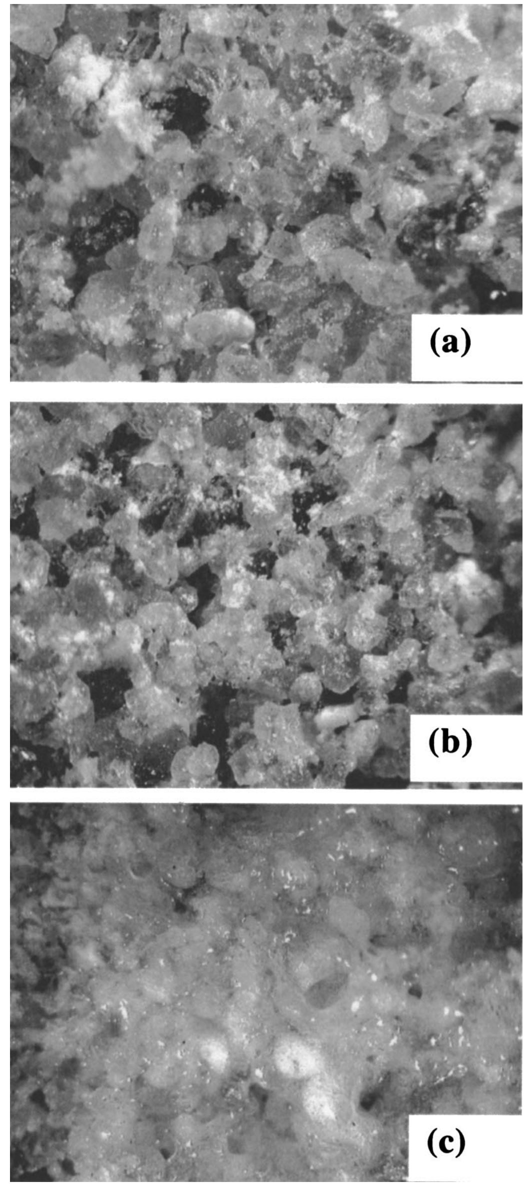

FIG. 5. High optical micrographs showing (a) the laser thermally spalled surface microstructure, (b) the mechanically saw cut surface, and (c) the laser molten surface.

had to be stopped before reaching the surface scorch zone. To clearly distinguish Zones II and III for Berea sandstone also disappeared in shale because of the composition difference of the rocks. Therefore, only three interaction zones are identified. They are Zone I: deep melting/strongly bonded glassy phase; Zone II: surface melting/cracked glassy layer, and Zone III: no visible melting/thermal spallation. Although the actual amount of removed weight for each individual zone was not measured, visual observation of the linear tracks revealed that Zone IV for Berea Gray sandstone and Zone III for shale have the most efficient material removal mechanism. The corresponding laser beam irradiance for producing the thermal spallation zones are around 920 W/cm^2 for Berea Gray sandstone and 784 W/cm^2 for shale. The laser parameters for specific energy measurement tests were selected from those two zones.

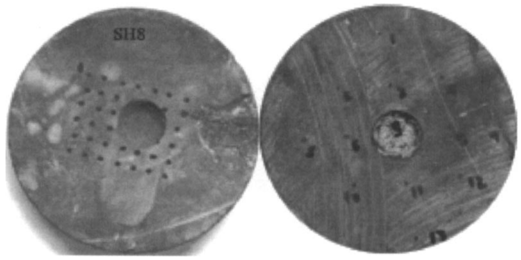

FIG. 4. Photographs showing the laser-drilled clear hole by thermal spallation (left) and hole with melted deposits by melting (right).

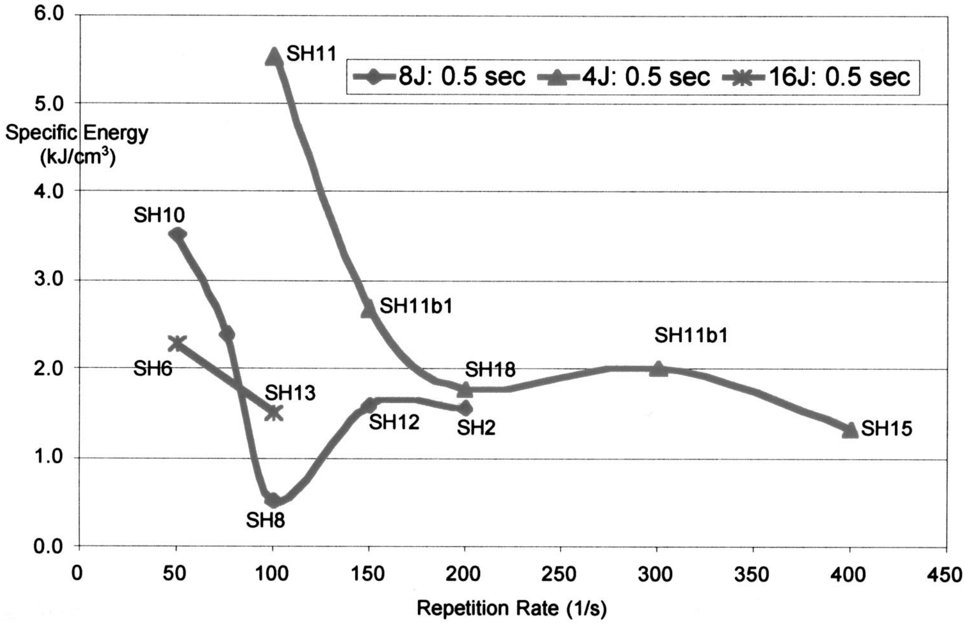

FIG. 6. Plots showing effects of repetition rate and energy per pulse on specific energy.

B. Specific energy tests

Figure 3 shows the specific energy for shale samples as a function of laser power under a fixed beam spot size of 0.5 in. and exposure time of 0.5 s. The SE results were grouped together by thermal spalling and melting identified by the physical reaction observed on the rock samples (Fig. 4). Thermal spalling produced a clear hole, and melting left melted deposits in the hole. At a very low power (200 W), the energy absorbed was only enough to heat up a small amount of rock and thermally fractured it; therefore, the SE is very high. As the power increased, a large volume of rock was heated up and fractured, resulting in small SE. This trend continues until the melting of rock started at a power over 600 W. There is a sharp increase of SE (from 0.5 to 2.2 kJ/cm^3) when the transition occurred from thermal spallation to melting. When laser photon energy is absorbed by the rock, thermal stresses first result when the change in dimensions of the locally heated rock as the result of a temperature change is prevented by surrounding cold rock. Then the thermal stress developed by a temperature change ΔT is

$$\sigma = \alpha E \Delta T, \tag{2}$$

where α = linear thermal coefficient of expansion and E = elastic modulus.

When the thermal stress rises to the rock's tensile strength, fracture or spallation of the rock occurs. Part of the absorbed laser energy is consumed by a new fractured surface in terms of surface energy.[8] The higher the rock temperature increased and the larger the thermal stress, then the greater the laser energy consumed in surface energy.

If the temperature rises above rock melting temperature, melting occurs. The laser energy E_1 required for melting a cylinder of diameter D and depth d_m is

$$E_1 = [c_p(T_m - T_0) + L_m]\rho d_m \pi D^2/4, \tag{3}$$

where c_p = heat capacity at constant pressure, T_m = melting temperature, T_0 = ambient temperature, L_m = latent heat of fusion, and ρ = density.

Therefore the thermal stress or surface energy for fracture and the melting energy for fusion are both proportional to rock temperature. The rock melting temperature is much higher than the temperature required to produce the threshold thermal fracture stress. Also for melting to occur, additional energy, latent heat of fusion, is required as shown in Eq. (3). In addition, quickly removing the solidified glass phase by the purging gas is more difficult. All these factors contribute to the sharp increase of SE when transition occurred from thermal spallation to melting.

Figure 3 also shows that SE decreased slightly in the melting zone as the laser power increased. This is believed to be due to the small reduction of the viscosity of the liquid phase at higher temperature[9] by higher power, and lighter liquid was easily removed from the hole by the purging gas. Laser–thermal fracture of rock, or spalling, can also be confirmed by comparing the micrographs of laser-spalled, mechanically saw-cut, and laser-molten rock at high magnification (Fig. 5). The optical micrograph of the thermal spalled sandstone [Fig. 5(a)] shows a similar remanded surface structure as the saw-cut surface [Fig. 5(b)] although the two have different rock fracture stress sources. The former gets the fracture stress from the temperature difference in the rock and the latter from the mechanical force. When the quart grains in the sandstone were molten by the laser pulses then solidified, they formed a glassy phase on the surface [Fig. 5(c)].

The effects of repetition rate and energy per pulse on SE are shown in Fig. 6. The group of 8 J/pulse has the smallest SE. At too high energy per pulse, for example 16 J/pulse, the rock would melt, therefore, SE increased. At too low energy per pulse, 4 J/pulse, a small volume of rock would be heated up and removed, leading to the same high SE. For the group of data lased with the same energy per pulse, 8 or 4 J/pulse, increasing repetition rate reduced the SE first in the thermal spallation zone, then increased the SE as the mechanism changed into melting. After melting started, the SE decreased slightly as repetition rate increased. As shown by points SH13, SH2, and SH15 in Fig. 6, it is very interesting to note that SE values were produced at a constant calculated laser power of 1.6 kW, but high energy per pulse and low repetition rate (SH13, 16 J/pulse, 100 l/s), medium energy per pulse, and repetition rate (SH2, 8 J/pulse, 200 l/s), and low energy per pulse and high repetition rate (SH15, 4 J/pulse, 400 l/s), were about the same. In other words, the same penetration rate could be achieved by using a different laser parameter combination. This can be explained by the following: in the thermal spalling dominant zone, two major factors that control the material removal rate are the maximum temperature (MT) and temperature cycling frequency (TCF). MT, largely controlled by the applied energy per pulse, determines the temperature difference (ΔT) in the rock, which in turn determines the thermal stress in the rock that is proportional to ΔT. When the thermal stress reached the static rupture strength of the rock, fracture of the rock occurred. Fracture of the rock could also occur at a stress that is lower than the rupture strength of the rock but cyclic from tension to compression. Increase of repetition rate of the laser beam would increase the cyclic frequency of the thermal stress and enhance the fracture. When the overall effect of MT and TCF was constant, the same SE results were expected. More systematic studies need to be done in the future to quantitatively characterize the laser-induced temperature and thermal stress field in the rock. Another contributor to the material removal is the laser-driven shock wave, which was detected by many researchers[10,11] and also by the current study. Increasing the repetition rate increased the intensity of the shock wave, therefore reducing the specific energy.

IV. CONCLUSIONS

Reservoir rocks can be removed by a high power laser beam through thermal spalling, melting, or vaporizing. However, thermal spallation is the most efficient rock removal mechanism that requires the smallest specific energy. As laser power increased, two rock removal zones, spallation and melting, were identified in the shale sample data with the least required SE of 0.508 kJ/cm^3 occurring at the point prior to melting.

The laser thermally spalled and saw mechanically cut rock shows similarity of surface microstructure.

The laser beam irradiance required for producing the thermal spallation zones is around 920 W/cm^2 for Berea gray sandstone and 784 W/cm^2 for shale.

Increasing beam repetition rate within the same material removal mechanism zone would increase the material removal rate due to an increase of the maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

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