Modeling Laser-Spallation Rock Drilling

High-power lasers can weaken, spall, melt, and vaporize Earth materials, with thermal spallation being the most energy-efficient rock-removal mechanism. The most interesting focus of recent laser rock-drilling research is on developing a laser rock-spallation technique to drill large and deep holes in rocks. Laser spallation has a rock-removal rate higher than conventional rotary drilling and flame-jet spallation. Research also is focused on the use of laser rock spallation to make perforation channels with improved permeability of the perforated rocks.

Introduction

Laser rock spallation is a rock-removal process that uses laser-induced thermal stress to fracture the rock into small fragments before it melts. High-intensity-laser energy, focused on a rock that has very low thermal conductivity, causes the local rock temperature to increase instantaneously. This results in a local thermal stress that spalls the rock. Previous test data show that laser rock spallation is the most energy efficient among all laser rock-removal mechanisms. Recent research and development cencentrating on use of advanced high-power lasers to drill and complete oil and gas wells has focused on two fronts. The first was to develop a multibeam laser rock-spallation technique to drill large and deep holes in rocks with a rock-removal rate higher than that of conventional rotary drilling and flame-jet spallation. In this approach, each laser beam spalls a hole as big as the beam spot and half the beam diameter deep. Multiple beams are overlapped to remove a layer of rock. Layer by layer, a large and deep hole is drilled. The second focus was to develop a laser rock-perforation technique for oil- and gas-well completion applications. Perforating oil and gas wells requires creating a hole through a composite structure of steel casing, cement, and formation rock. Current explosive-charge perforation methods, while capable of creating the holes, significantly reduce the rock permeability. Laboratory tests demonstrate that laser beams not only cut rocks efficiently, but also increase the permeability of spalling-drilled rock significantly. An innovative laser perforating system will allow the oil and gas industry to improve injection and production rates.

Laser rock spallation is a very complex phenomenon that depends on many factors. Simply relying on experimental studies to understand this phenomenon could be costly and time consuming. Because currently available techniques cannot quantitatively assess some of the factors, it may be impossible to study these factors by experimental means alone. Computer modeling can establish a virtual experiment and simulate the action of the factors that are difficult to study in the laboratory. Modeling laser/rock interaction is complex because: (1) traditional heat transfer and rock mechanics theory do not apply because rock is a porous medium, (2) the laser rock-removal process involves a variety of physical phenomena such as porous flow, elastic thermal fracture, phase change, and purging gas flow, and (3) thermal-physical-property data for rocks are lacking, particularly data at elevated temperatures. A combined approach is proposed to this complex problem—that is, establishing models for each of the physical phenomena on the basis of the finite-difference method (FDM), then combining them into one numerical procedure using the constrained-interpolation-profile (CIP) method and the CIP combined-and-unified-procedure (CCUP) method. CCUP, based on FDM, is developed to simulate large deformations of materials, fragmentation, multiphase problems, and fluid/structure interaction problems. With this approach, the transient temperature and stress distributions in dry or water-saturated rocks exposed to a laser beam can be calculated. The spallation boundary and rock-removal energy efficiency have been determined for

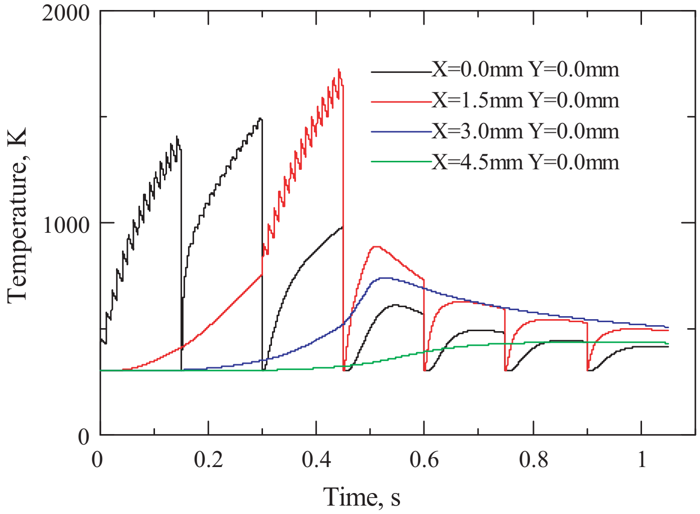

Fig. 1—Transient temperature behavior.

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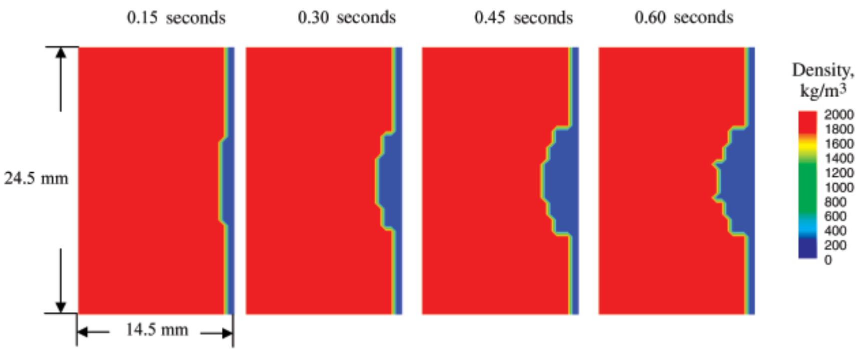

Fig. 2—Spatial density distribution.

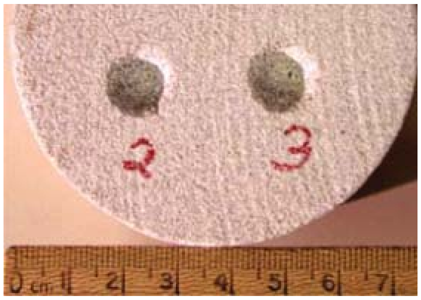

Fig. 3—Two 10×4-mm holes in sandstone spalled by an 800-W 0.5-second pulsed laser beam.

different laser conditions. The modeling results provide a better understanding of the laser rock-spallation phenomenon and, most importantly, guidelines for selecting processing parameters for fast rock removal.

Mathematical Modeling

In this study, the laser spallation of Berea gray sandstone by a pulsed laser beam is considered. For simplicity, the rock is divided into small 0.5×0.5-mm meshes. Each mesh is assumed to be composed of quartz, air, aluminum oxide, and iron oxide with a certain fraction of each) and behaves like isotropic-elastic material. The numerical modeling system and a schematic of an enlarged mesh are shown in Fig. 1 in the full-length paper. The input laser beam spot size is assumed to be 10 mm in diameter.

The CCUP method, which is compact and has a low calculation cost, is used to solve the stress and governing equations for the temperature and stress distributions in the rock spalled by a pulsed laser beam. In addition, laser spallation removal of rock was simulated by calculating the temperature and stress distributions on the basis of the new boundary conditions inherited from the previous timestep.

Numerical Results

The thermal models described in the full-length paper were used to calculate the stress and temperature distributions in Berea gray sandstone, from which the spallation boundary and spallation efficiency were determined. The pulsed laser beam was applied to the rock in bursts. One laser burst consisted of 0.5-second laser "on" time and 1-second "off" time. During the 0.5-second laser on time, the number of laser pulses applied to the rock depends on the pulse repetition rate. For example, at a 100-Hz pulse repetition rate, the rate simulated in this study, the number of laser pulses applied during 0.5 seconds is 50. The rock will spall when the stresses established in the rock satisfy the spallation conditions. The time interval for rock spallation is set at 0.15 seconds. In other words, rock removal by laser spallation occurs every 0.15 seconds.

Fig. 1 shows the transient behavior of rock temperature at different rock locations lased by one burst of a Gaussian laser beam of 800-W average power and 1-ms pulse width. In Fig. 1, the position X=0.0 mm and Y=0.0 mm represents the center of the initial laser irradiation spot. Temperatures at X=0.0 and 1.5 have periodic increments and a decreasing profile like the teeth of a saw. These sawlike profiles result from periodic heat input from repeated laser irradiation. For one laser pulse, the rock warms during the first 1 ms and cools during the next 9 ms because of heat conduction of the rock and heat convection of ambient gas such as air. However, net heat input is positive, so temperature increases as time passes. These two profiles periodically become 300 K at each 0.15-second rock-spallation interval. This is because temperature is forced to be 300 K where stresses satisfy spallation conditions to simulate the spallation rock removal and introduction of fresh air to the new rock surface. The temperature of the fresh air is 300 K. For rock locations far away from the center of the initial laser radiation spot, temperatures do not have sawlike profiles. This is because rock thermal conductivity is small and heat transfer is poor. That is, far from the irradiation spot, the effect of high-repetition laser irradiation is insignificant.

Fig. 2 shows the spallation boundary. The red region represents the rock, and the blue region represents the laser-spalled rock hole filled with air. The time intervals for the four pictures from left to right are 0.15, 0.30, 0.45, and 0.60 seconds, respectively. The shape of the spallation hole nearly corresponds to the spatial distribution of the laser profile (i.e., a Gaussian profile). However, heat diffusion of heat conduction based on Fourier's law also has a profile similar to the spatial distribution of the spallation hole. At this stage, it is difficult to conclude which is the dominant cause. The diameter of the spallation hole nearly corresponds to that of the laser-radiation-spot size, 10.0 mm. The depth of the hole is 3.0 mm. This simulated depth of spalled hole is slightly less than the 4.0-mm actual hole depth spalled by a laser beam shown in **Fig. 3.** Primarily, this is because the simulation model does not account for the additional rock removal resulting from the purging gas and in-pore water vaporization pressure.

Fig. 8 in the full-length paper shows energy efficiencies for laser spallation under three laser-parameter cases. For one laser burst, the spallation efficiency of 0.45 seconds is the best among energy efficiencies for 0.15, 0.30, 0.45, and 0.60 seconds. As time passes, heat propagates from the surface to deeper parts of the rock. Heat propagates faster than the spallation boundary. Therefore, the laser energy needed to spall the rock heated by previous laser pulses decreases as time passes. For times greater than 0.45 seconds, slight melting of rock started, resulting in efficiency reduction. This is another indication that a relaxation time is needed between the laser bursts to avoid rock melting. This implies that future laser on time for a laser burst should be set at 0.45 seconds for best energy efficiency.

Conclusions

A 2D model was used to simulate laser-spallation rock removal of Berea gray sandstone by a pulsed laser beam. The transient and spatial distributions of temperature and stresses were calculated by use of a model. The spallation boundary and energy efficiency were determined. The dimensions of the numerically simulated spallation hole were very close to those of the actual laser-spalled hole under the same laser conditions. JPT