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Numerical Modeling of Laser Perforating Process in Anisotropic and Heterogeneous Materials

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ABSTRACT

In this study we numerically characterize the physical dynamics, heat transfer and thermal-mechanical interactions, induced by high-power laser irradiation in anisotropic heterogeneous rocks. Towards developing an integrated and predictive numerical framework for downhole laser operations, the heat transfer and thermal-mechanical process of laser-rock interaction is modeled a three-dimensional continuum mechanics software (FLAC3D). The mechanical behaviors of reservoir rocks are modeled by elastic-plastic constitutive model. Laser beams are applied as a boundary heating sources. The transient heat transfer and storage in materials, and development of thermally induced displacements and forces are simulated by the thermal module in FLAC3D. A phase change module is developed to handle the phase changes (i.e., melting and vaporization) during the heating process. The dependence of rock properties on temperature is measured in laboratory experiments. The directional and spatial variations of rock properties and discontinuities (randomly distributed heterogeneity, ubiquitous joints, and discrete fractures) on the laser penetration rate and mechanical damage are extensively investigated. Simulations indicated that, due to strong heating intensity of the laser beam, the temperature gradient near sample surface is extreme; therefore, causing a sudden thermal expansion in the timescale of milliseconds, which transforms the stress from compressive to tensile. When the tensile stress exceeds the tensile strength, tensile cracking occurs. Since the heating intensity decays exponentially away from the heating center under the laser beam, the stress in the area near the heating source changes more rapidly than other areas, resulting in non-uniform stress distribution. As shear stress overshoots the shear strength of the rock, shear yielding and shear slip takes place. It was also observed that the confining stress has more pronounced effect on the shear failure than tensile failure. The influence of the weak discontinuities on the mechanical damage is more dependent on their orientations. The simulations in this study provide important insights to how to control laser-rock interaction, enhance experimental prototypes and advance the design of a comprehensive numerical tool for laser drilling and downhole laser operations.