PORE FLUID ENHANCED THERMAL SPALLATION OF ROCK: A NUMERICAL STUDY

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Abstract: Thermal spallation of rock, i.e. the fragmentation of rock surface material under rapid external heating, is numerically studied here. A special emphasis is laid on the possibility that the fluid in the micro-pores of rock enhances the spallation due to rapid thermal expansion. For this end, a numerical model based on the embedded discontinuity finite element approach to rock fracture and an explicit scheme to solve the underlying thermo-mechanical problem is developed. The fluid trapped into the micro-pores is modelled as a material that can bear only volumetric compressive stresses. A thermal spallation problem of a rock sample under axisymmetry is simulated as a numerical example. According to the simulations, the potential presence of the pore-fluid significantly boost the spallation events.

Keywords: thermal spallation, rock fracture, pore fluid, embedded discontinuity, finite elements

1. Introduction

Rock and concrete materials surface layer fragments and ejects out (spalls) as illustrated in Fig. 1a, when exposed to a rapid external heating. This phenomenon, called thermal spallation, can be utilized in non-mechanical breakage, comminution and crushing, of these materials. Moreover, if the material has fluid trapped in micro-pores, it enhances the spalling due to rapid expansion of the pore-fluid (see Fig. 1a) [1]. Here, a numerical study on the pore-fluid enhanced thermal spallation of rock is presented.

For this end, the finite element based numerical method presented in [2] is exploited to test the effect of the pore-fluid. In this approach, the rock fracture is modelled by the embedded discontinuity finite elements. Moreover, the material properties are assumed to be temperature independent in this preliminary study. A numerical example of heterogeneous granitic rock under a high intensity heat flux is solved with and without pore-fluid under axisymmetric conditions.

2. Numerical approach

The finite element discretized uncoupled thermo-mechanical problem underlying the thermal spallation of rock is

$$\boldsymbol{M}_\theta\dot{\boldsymbol{\theta}} + \boldsymbol{K}\boldsymbol{\theta} = \boldsymbol{f}_q,\ \ \boldsymbol{f}_q = \boldsymbol{A}_{e=1}^{Nele}\int_{\Gamma_q^e}\boldsymbol{N}_\theta q_n d\Gamma \tag{1}$$

$$\boldsymbol{M}_u\ddot{\mathbf{u}} + \boldsymbol{f}_{int} = \boldsymbol{f}_{ext},\ \ \boldsymbol{f}_{int} = \boldsymbol{A}_{e=1}^{Nele}\int_{A_e}\boldsymbol{B}_u\boldsymbol{\sigma} dA \tag{2}$$

where $\boldsymbol{\theta}$, $\boldsymbol{M}_\theta$, $\boldsymbol{K}$, $\boldsymbol{f}_q$, and q_n are the nodal temperature vector, the capacitance matrix, the conductivity matrix, the external heat vector, and the heat flux, respectively. Moreover, $\mathbf{u}$, $\boldsymbol{M}_u$, $\boldsymbol{f}_{int}$, $\boldsymbol{f}_{ext}$ are the nodal displacement vector, the mass matrix, the internal and external force vectors, respectively. This system is solved with and explicit time integration by solving the temperature field in (1) first, and then solving the thermal stress induced damage and the stress tensor at the element level resulting in the internal force vector for the mechanical system (2). Finally, the mechanical system is solved. The stress-strain relations for the rock and pore-fluid are, respectively,

$$\boldsymbol{\sigma} = \boldsymbol{E}:\left(\boldsymbol{\varepsilon} - \boldsymbol{\nabla}N^{sol}\otimes\boldsymbol{\alpha}_d - \boldsymbol{\varepsilon}_\theta\right),\ \ \boldsymbol{\varepsilon}_\theta = \alpha\Delta\theta\boldsymbol{I} \tag{3}$$

$$\boldsymbol{\sigma} = K_{bulk}(\varepsilon_{vol} - \alpha\Delta\theta)\boldsymbol{I} \tag{4}$$

where $\boldsymbol{E}$, $\boldsymbol{\varepsilon}$ are the elasticity tensor and total strain tensor, $\boldsymbol{\varepsilon}_\theta$ is the thermal strain, α is the thermal expansion coefficient, $\boldsymbol{I}$ is the second order identity tensor, K_{bulk} is the bulk modulus, and ε_{vol} is the volumetric strain. Finally, $\nabla\boldsymbol{N}^{sol}$ and $\boldsymbol{\alpha}_d$ are the kinematic operator and the displacement jump vector related to the discontinuity model. This model is formally similar to the plasticity models with the distinctive feature that it accounts for crack orientation. For more details, see [2].

3. Numerical simulation

The problem of thermal spallation is simulated under axisymmetry with the mesh and axisymmetry illustrated in Fig. 1c. The heat flux value is 3E6 J/m^2 with the heating time of 0.1 s. The rock is modelled as heterogeneous material with the mineral structure illustrated in Fig. 1b. Some of the elements are assigned to the pore-fluid with the material properties of water. The simulation results are shown in Fig. 1d-g.

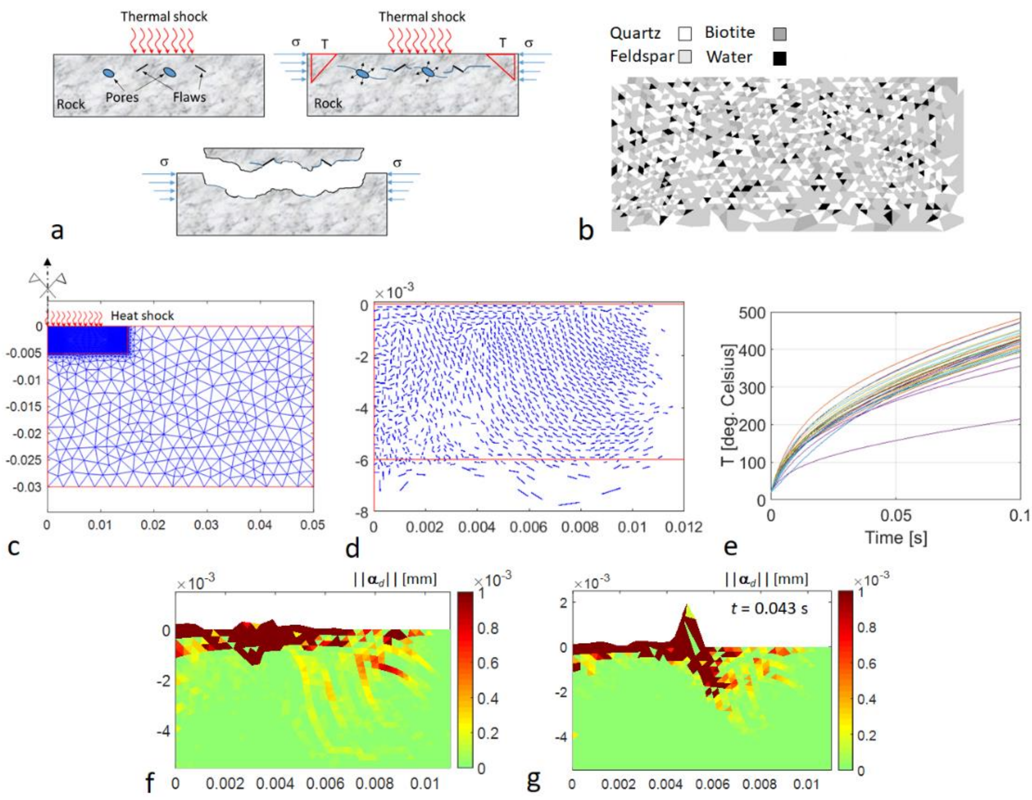

Fig. 1. Principle of pore-fluid enhanced spallation a), numerical rock mineral structure b), mesh and boundary conditions (3k CST elements) c), predicted crack orientations d), surface node temperatures e), crack opening magnitude without pore-fluid f), and with pore-fluid g).

The predicted cracks are parallel to the rock surface in the narrow strip that is under compression. However, their orientation turns to vertical immediately outside the narrow compression zone. The temperatures reached at the surface nodes subjected to the heat shock are around 400 °C. This temperature results in spallation at the end of heating, as illustrated in Fig. 1f. With the pore-fluid, the spallation takes place already at t = 0.043 s. Therefore, the presence of pore-fluid clearly facilitates the spallation.

4. Conclusions

The thermal spallation of concrete is substantially facilitated by the thermal expansion of the pore-fluid. The present numerical simulations show that this is also the case with the granitic rock. However, further numerical investigations should be carried out with a more refined model that takes into account the temperature dependence of the rock mechanical and thermal properties.

References

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