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Mechanics of edge crack growth under transient pressure and temperature conditions

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ABSTRACT

The propagation of an edge fracture under compression in a semi-infinite impermeable isotropic elastic solid, subject to suddenly applied internal fluid pressure and temperature change, is studied numerically. The process involves a strong coupling between the elastic deformation, heat conduction in solids and fluid transport in fractures. Fluid flow is described by the lubrication equation, while the fracture width and fluid front are affected by thermal stresses and fluid pressure. Numerical results are provided for the cases where the cooling-induced tensile stress can overcome the compressive stress across the crack to propagate it at a thermally controlled speed, which is larger than the speed for crack growth resulting only from applied pressure. The presence of the pressurized fluids can result in crack growth starting earlier and can produce a slow early time crack speed. As time increases, the crack motion is accelerated by the pressure acting in the fracture from the viscous fluid flow toward the crack tip. The crack growth rate varies over a wider range relative to a pure thermally driven crack growth case and a stable, rapid growth period occurs, during which the calculated crack speeds are consistent with experimental results. The crack growth curves are located in between two thermally controlled ones for the fracture with and without uniform pressure, respectively. In addition, the dimensionless factors controlling the hydrothermal crack growth are derived from a dimensional analysis. Numerical results demonstrate that viscous flow which leads to the fluid front lagging behind the crack tip can stabilize crack growth under a larger temperature change.

1. Introduction

Brittle cracking driven by thermal contraction of a hot rock subject to cooling is important, not only because of the observed related geological phenomena such as contraction cracks in basalt, permafrost and mud, but also because the cooling is often provided by fluid circulation and in that case there is a strong coupling with pressurized fluids that affects the rock mass permeability and strength variations during the course of circulation (e.g., Lachenbruch (1961), Wiederhorn, (1968), Lister (1974), Scholz (1968), Martin (1972), Martin and Durham (1975), Norton et al. (1984), and Rovetta (1993)). The cooling-induced tensile stress can increase crack surface displacements, length and interconnection in a hydrothermal system, thus increasing the fractured rock mass permeability. Seismic events associated with Icelandic geothermal areas at a depth of 7 km have been reported by Ward (1972) as being created by rapid cooling of the rock by water. Thermal contraction of hot rocks is also an important mechanism for the development of fractures near the magma-rock interface of a mid-ocean ridge magma chamber (Norton et al., 1984; Rovetta, 1993). Recent work has considered the effect of circulation of cold water or CO_2 through a reservoir, causing the rock to contract, creating tensile stresses and potentially leading to the nucleation of new cracks (Bourdin et al., 2011; Goodarzi et al., 2013; Tarasovs and Ghassemi, 2014). Although some studies treat the penetration of water in thermally cracked hot dry rock as flow in an equivalent porous media, introducing an anisotropic permeability along the directions parallel and normal to the fissure systems (Rabinowicz et al., 1999), study of discrete fracture growth in a hydrothermal system is worth more attention since development of thermal contraction fractures, which sometimes is a main contributor to rock permeability (Rovetta, 1993) and nonlinear creep behaviors (Martin, 1972), is likely affected substantially by the localized deformation. In addition, in the oil and gas industry, cooling of the rock around the wellbore is likely to play an important role in hydraulic fracture initiation at multiple sites during shale gas stimulations (Tran et al., 2010).

Instead of investigating the formation and instability of thermally activated multiple interacting crack patterns (Bažant and

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Nomenclature

Symbol	*Description (unit)*
a, a_0	Crack length and initial crack length (m)
C	coefficient in the power-law obtained by Martin (1972)
E, E'	Young's modulus and plane strain modulus (MPa)
G, $\tilde{G}$	Green's function and normalized Green's function
h, $\tilde{h}$	weight function and normalized weight function
K_I, K_{Ic}	mode I stress intensity factor and fracture toughness (MPa$\sqrt{\text{m}}$)
n	index in the power-law obtained by Martin (1972)
p_f, p_0	fluid pressure along the fracture and at the fracture mouth (MPa)
q	2D fluid flux (m^2/s)
s	vertical coordinate (m)
t	time (s)
T	scaling time (s)
ΔT, ΔT_0	temperature change and specified temperature drop on the edge (K)
w, w_0	fracture opening and initial fracture aperture (m)
x, y	coordinates (m)
α	thermal expansion coefficient (1/K)
ε	small number and controlling parameter
ϕ	$= \gamma/(2\sqrt{\tau})$
Γ	normalized fluid flux
γ, γ_0	normalized fracture length and normalized initial fracture length
η	normalized temperature
κ	thermal diffusivity (m^2/s)
μ	dynamic viscosity (MPa s)
ν	Poisson's ratio
Π, Π_0	normalized fluid pressure along the fracture and at the fracture mouth
ϖ	scaling fluid flux (m)
ρ	$= y/a$
σ	normal stress across the fracture (MPa)
σ_0	remote normal stress in x direction (MPa)
σ_{ij}^{th}, $\sigma_{\max}^{th}$	thermal-induced stress components and maximum thermal-induced normal stress along the fracture (MPa)
Σ	normalized normal stress across the fracture
Σ_0	normalized remote normal stress in x direction
τ	normalized time
ω	scaling fracture opening (m)
Ω	normalized fracture opening
Ω_0	normalized initial fracture aperture
ℓ	scaling length (m)

Ohtsubo, 1978; Nemat-Nasser et al., 1978; Goehring et al., 2009; Bažant et al., 2014; Tarasovs and Ghassemi, 2014), we consider the growth of one single edge fracture, subject to a constant far-field confining stress, from the surface of a semi-infinite elastic medium, in the presence of thermal stress and constant water pressure. The conditions used are sufficient to grow the fracture as a result of development of a transient temperature field and associated thermoelastic stress changes, and the growth rate is enhanced by penetration of pre-existing pressurized fluids (Martin, 1972; Lister, 1974). The problem of brittle fractures growing into a semi-infinite medium stressed at its surface has been studied thoroughly by Lachenbruch (1961) and water penetration and pressure has been considered by Lister (1974), although most of the previous models are independent of fluid transport (Norton et al., 1984; Tarasovs and Ghassemi, 2014; among others). Most of these analyses concluded that crack propagation has little effect on the temperature field. We here address the same problem as studied by Lister (1974), in which the stable propagation solutions under the combination of thermal stress and fluid pressure are found. In contrast to the essentially static fluid pressure as assumed by Lachenbruch (1961) and Lister (1974), the fluid pressure inside the fracture is not assumed a priori, but evolves in the present work with the crack propagation.

The experimental study by Martin (1972) concerning an isolated axial crack in single-crystal of quartz loaded in a steel vessel containing steaming water with a known pressure, subject to different temperature changes, delineated the importance of the time-dependent growth of axial cracks and the manner in which the water is transported to the fracture tip, which differs from the chemical reaction dominated creep of rocks occurring in stress corrosion (Wiederhorn, 1968). Martin's experimental results indicated that the rate of crack growth increases if any of the three variables of temperature, stress or pressure increases. Martin (1972) proposed an explicit formula based on the Arrhenius plots to quantify the effects of these parameters on the crack velocity. A power law relationship between the crack length and time was extracted from his experimental data, with the index ranging from 0.2 to 0.8. Martin and Durham (1975) further revealed that there is no plastic deformation at the fracture tip in quartz-based rocks up to a temperature of 250 °C and the experimental results appear independent of microstructure changes that occur during Dauphine twinning. However, these results show the importance of mechanical coupling of stress- and thermal-induced rock deformation and fluid flow. The nonlinear (creep) responses in failure strength can be attributed to the time-dependent crack growth in brittle materials (Martin and Durham, 1975). Cracking within the framework of elasticity is therefore the principal model for the overall mechanical behavior of these rocks. Martin and Durham (1975) further confirmed that the stress level for the crack growth in silicate rocks with water pressurizing the fracture is reduced by one order of magnitude below that for silicate rocks with no water available. From their observations, some nonlinear material responses under different environments, which can exist on a variety of length scales (Rice and Rundicki, 1979; Segall, 1984), can be explained by time-dependent crack growth in brittle rocks. Hence, more attention should be paid to the coupled mechanical responses instead of attributing the nonlinear responses solely to microstructural changes.

The transient fracture behaviors in the presence of both pressurized fluid and transient thermal stress in a rock have not yet been fully explored theoretically, although some interesting experimental results have been reported by Martin (1972) and Martin and Durham (1975). To the authors' knowledge, time-dependent fracture growth under multiple environmental variations such as fluid pressure and temperature has not been fully explored. In this paper, we will make use of a coupled model of the rock deformation, fluid flow and thermal conduction to investigate the time-dependent fracture growth, opening development and pressure evolution of a single edge fracture extending from the free surface of a semi-infinite rock medium. In particular, we will revisit some of the conclusions drawn by Martin (1972) and focus on the rate of the crack growth in relation to other quantities of physical interest such as the material parameters, initial fracture lengths and conductivities, as well as the inlet fluid pressure.