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Thermal-hydro-mechanical coupling stress intensity factor of brittle rock

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Abstract: A new calculation formula of THM coupling stress intensity factor was derived by the boundary collocation method, in which an additional constant stress function was successfully introduced for the cracked specimen with hydraulic pressure applied on its crack surface. Based on the newly derived formula, THM coupling fracture modes (including tensile, shear and mixed fracture mode) can be predicted by a new fracture criterion of stress intensity factor ratio, where the maximum axial load was measured by self-designed THM coupling fracture test. SEM analyses of THM coupling fractured surface indicate that the higher the temperature and hydraulic pressure are and the lower the confining pressure is, the more easily the intergranular (tension) fracture occurs. The transgranular (shear) fracture occurs in the opposite case while the mixed-mode fracture occurs in the middle case. The tested THM coupling fracture mechanisms are in good agreement with the predicted THM coupling fracture modes, which can verify correction of the newly-derived THM coupling stress intensity factor formula.
Key words: stress intensity factor; thermal-hydro-mechanical coupling; boundary collocation method; fracture mechanism; brittle rock

1 Introduction

In deep exploitation of minerals and oil, geothermal development, nuclear waste disposal and underground energy storage, brittle rock is usually subjected to thermal-hydro-mechanical (THM) coupling condition and THM coupling fracture easily occurs, which attracts more and more attentions of researcher [1−3]. It is very important to calculate stress intensity factor for determining fracture mode in study of THM coupling fracture [4,5]. Currently, available literatures of coupling stress intensity factor calculation are only focused on thermal-mechanical (TM) or hydro-mechanical (HM) coupling condition. For example, weight function method [6,7] and interaction integral method [8] were used to deduce TM coupling stress intensity factors of the semi-elliptical crack, circumferential crack and three dimensional curved crack. Scaled boundary finite element method [9], Geertsma's model method [10] and superposition principle method [11,12] were applied to calculating HM coupling stress intensity factors of the opening crack and compressive-shear crack. Although there are very few literatures on the simulation of THM coupling fracture process by using virtual multi-dimensional internal bonds method [13] and hybrid finite difference-displacement discontinuity method [14], there is lacking in study of THM coupling stress intensity factor.

In this study, the traditional boundary collocation was used to deduce THM coupling stress intensity factor formula by firstly introducing an additional constant stress function, since this method was only suitable for calculating stress intensity factor of the cracked specimen without any force on its crack surface. THM coupling fracture mode (including tensile, shear and mixed mode fracture) could be predicted by a new criterion of stress intensity factor ratio and self-designed THM coupling fracture test. THM coupling fracture mechanism was revealed by analyzing microscopic characteristics of fractured surface and compared with the predicted THM coupling fracture mode in order to verify the newly-derived THM coupling stress intensity factor formula.

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2 Derivation of THM coupling stress intensity factor

2.1 Calculation model

A standard cylinder specimen (D=50 mm, L=100 mm) was adopted (Fig. 1), with an inclined penetrating crack of $2a$=30 mm and α=45° and subjected to THM coupling condition (i.e., temperature t, hydraulic pressure p_H, confining pressure p_M and axial pressure p_L). Table 1 shows different THM coupling conditions for calculation, where the axial pressure was unit pressure (p_L=1 MPa) and the hydraulic pressure (p_H) must be smaller than the confining pressure (p_M) in order to avoid the mixture of water and oil. The temperature must be controlled within 100 °C for preventing evaporation of water, since actual temperature in deep mining is lower than 100 °C. Δt, α, and E_T were temperature difference between room temperature and tested temperature, thermal expansion coefficient and elastic modulus, respectively.

2.2 Formula derivation

2.2.1 Stress function

As shown in Fig. 1, a global rectangular coordinate system (XOY) was set at the center of crack surface (O), and a local rectangular (xoy) and a polar (ox) coordinate systems were set at the crack tip (o).

The boundary collocation method was applied to calculating stress intensity factor of the cylinder specimen under THM coupling condition, where a biharmonic stress function must be chosen appropriately to meet all boundary conditions. Generally, the stress function (φ_1) is in the form of series expansion only for the crack without applied force on its surface. For the THM coupling specimen with the hydraulic pressure p_H (Fig. 1), it is necessary to introduce an additional constant stress function (φ_2). The stress function φ is written as the sum of φ_1 and φ_2.

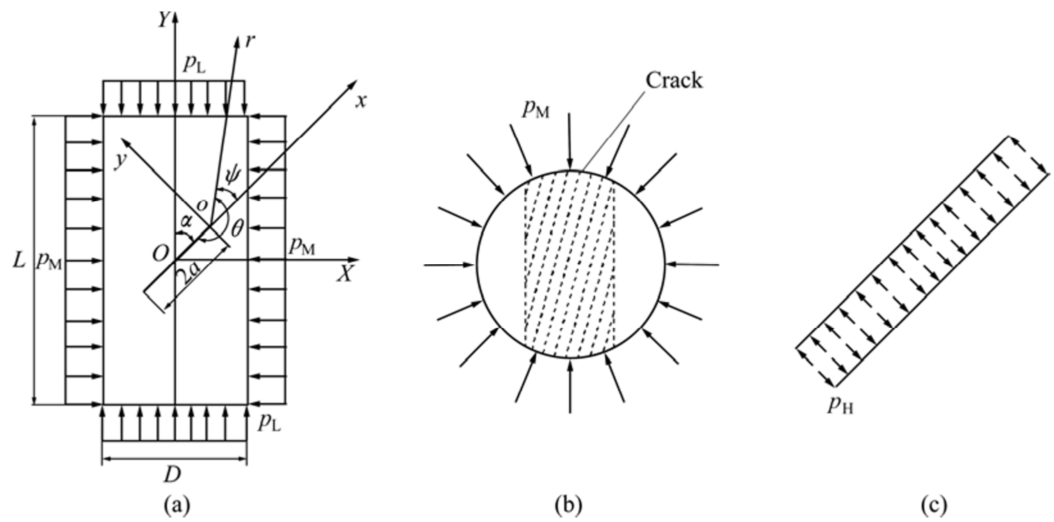

Fig. 1 THM coupling calculation model: (a) Front view; (b) Top view; (c) Enlarged crack surface

Table 1 THM coupling loading condition

No.	t/°C	Δt/°C	α/°C	E_T/GPa	p_L/MPa	p_H/MPa	p_M/MPa
T1	25	0	5×10^{-6}	10.67	1	2	4
T2	50	25	5×10^{-6}	10.54	1	2	4
T3	70	45	5×10^{-6}	10.50	1	2	4
T4	90	65	5×10^{-6}	10.48	1	2	4
H1	70	45	5×10^{-6}	10.50	1	1.5	4
H2	70	45	5×10^{-6}	10.50	1	2.5	4
H3	70	45	5×10^{-6}	10.50	1	3.5	4
M1	50	25	5×10^{-6}	10.54	1	2	2.5
M2	50	25	5×10^{-6}	10.54	1	2	3
M3	50	25	5×10^{-6}	10.54	1	2	4.5