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T–M coupled effects on cracking behaviors and reliability analysis of double-notched crustal rocks

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ABSTRACT

Experiments on crack initiation and propagation of double-notched rocks caused by thermal–mechanical loading were carried out by using *in-situ* SEM observation technique. The results indicated that thermal-induced or thermal–mechanical-induced cracking mechanisms depend strongly on thermal deformation mismatch between the mineral compositions. Micro cracks initiation occurred mainly in the harder and larger quartz grains, but the failure strength of rock did not adequately degrade when surface micro crack density is less than 40 (mm^{-2}). At last, a reliability analysis of 3-parameter Weibull distribution model is presented to discuss the effect of the thermal-induced micro crack on failure strength of rock. Threshold value by thermal-induced micro crack density to influence on the failure strength of crustal rock can be estimated at about 50–60 (mm^{-2}).

1. Introduction

Crustal rocks are typical brittle materials with a low strength and low fracture toughness, and they may generate some plastic deformations under three-dimensional (3D) stress states or at elevated temperatures. Different evaluated damage models and induced factors of crustal rocks have attracted many attentions from scientific community. Especially those applications for deep mining and petroleum exploitation in which considerable reliability and security were required [1–4]. For example, the temperature of the confining rocks around a nuclear waste repository will reach approximately 250–300 °C after 200–300 years [5]. Based on an average geothermal gradient (3 °C/100 m) of crustal rocks, the highest temperature may only reach 100–150 °C at the depth of 3000–5000 m which is the relevant depth for geothermal resources.

The effects of the elevated temperature from 100 °C to 250 °C on damage behaviors of crustal rocks or sandstone concrete at macroscopic scales were studied by numerous investigators [1,6–11], in which indicated that there were different failure strengths of crustal rocks at different elevated temperatures. The probability of failure strength mainly depends on statistical approaches, the distribution of defects (including the thermal-induced cracks) and the mineral particles size of crustal rocks. However, until now little literature has been available on the thermal-crack initiation and propagation behavior of crustal rock and crack evaluations at different elevated temperatures. Especially, the effect of thermal-induced cracks on the failure

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Nomenclature

ρ	surface micro crack area density, m^{-2}
N_i	amount of thermal-induced micro crack
A	observation area, m^2
F	probability of failure strength of crustal rock for a given x value
a	shape parameter
b	scale parameter
c	location parameter
x	ultimate tensile strength, MPa
$\widehat{F}(x_i)$	cumulative distribution function
n	experimentalgroup number
X_i	tensile testing data at the different elevated temperatures
$\widehat{X}$	the expected value of failure strength data
ρ'	correlation coefficient
$E(x)$	expected value
$S(x)$	standard deviation
R	reliability index of a probability distribution function
T	elevated temperature, °C

strength of crustal rocks was seldom reported in the past decades in which scattered strength data was usually observed. Therefore, it is proposed that significant issues related to rock nonlinear mechanics, or treatment methods of scattered failure strength data should be considered as a multi-scale damage model. In addition, current studies are lack of enough experimental researches in the thermal-induced cracking behavior, their influence factors and the failure strength prediction model of crustal rocks. Probabilistic models are chosen for the current study because they cannot only help to understand the physical significance of failure, but also enable one to predict, quantify and assure its failure performance in the field [12,13].

In this study, we try to improve the estimation method of failure strength based on the SEM *in-situ* observations, tensile-displacement curves of crustal rocks at different temperatures in order to understand the influence of thermal–mechanically induced crack initiation behavior on the failure strength of crustal rocks.

2. Material and experimental procedure

2.1. Material

All double-notched specimens used in these tensile tests were prepared from a big sandstone block which was taken from 1150 m deep underground at Pingdingshan Henan province in the mid-eastern region of China. The mineral compositions of this crustal rock were listed in Table 1 by using X-ray diffraction (XRD) detecting method. The density and porosity of this original rock are about 2.6 g cm^{-3} and $(1.5–3.8) \times 10^{-2}$ [4].

2.2. Experimental procedure

The flat dog-bone shaped specimens with a 20 mm gage length and a 1.4 mm by 2.5 mm gage cross-section as shown in Fig. 1a were tested at five temperatures 25 °C, 150 °C, 200 °C, 250 °C and 300 °C on the JSM-5410LV SEM and hydraulic servo-high temperature testing system of Shimadzu Corporation, Japan [14–16]. The artificial double edge notches were cut in the middle of each testing specimen with the approximate notch radius and depth at about 0.2 mm (Fig. 1b) in order to produce a stress concentration by artificial factors [17]. The free surfaces of all testing specimens were carefully polished by abrasive paper (P1000) to achieve an approximate surface roughness of R_a = 0.35–0.45 μm. The observation surface of each specimen was deposited by a gold spraying method in order to clearly show the morphology of surface by using SEM *in-situ* technology. The signal of SEM can be directly transferred to a computer via a direct memory access type A/D converter, and photos with 960 × 1280 frames can be directly seen on the computer screen.

Table 1
The mineral compositions of crustal rock (wt.%).

	Quartz	Potassium feldspar	Calcite	Dolomite	Siderite	Clay
Sample 1	54.70	17.00	2.00	3.60	3.10	Balance
Sample 2	56.10	17.40	1.20	1.90	3.00	Balance