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Investigation on mechanical properties and damage evolution of coal after hydraulic slotting

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ABSTRACT

Hydraulic slotting technique has been widely adopted in China for underground enhanced coal bed methane (ECBM) recovery. However, the related fundamental research of this technique is insufficient enough to get a comprehensive understanding of its action mechanism. In the current work, numerical models of specimens with various flaw inclination angles are built with particle flow code in two dimensions (PFC^{2D}). The relationship between mechanical properties and flaw inclination angle is analyzed, and the results show that (1) with an increase in the flaw inclination angle θ, the peak axial strain appears a decreasing trend after an initial increase and the peak lateral strain decreases gradually. With regard to the peak volumetric strain, when $\theta < 30^\circ$, it is positive, which implies that the specimen is in the state of volume shrinkage. In contrast, when $\theta > 30^\circ$, the peak volumetric strain is negative and the dilatancy occurs. (2) The elastic modulus and the initial damage coefficient show opposite variation trend with θ. Both of the relationships satisfy the Boltzmann function. (3) The peak strength and the initiation stress increase with θ. Furthermore, the damage constitutive equation of specimens with different flaw inclination angles under uniaxial compression is established with the consideration of the initial damage, loading damage, the stress–strain curves and crack number. The theoretical curves match well with the numerical curves and the achievements reported by other authors. The results of this study are expected to provide crucial guidance for the application of hydraulic slotting in ECBM recovery.

1. Introduction

Gas disaster, a major problem faced by the mining industry in China, is a great threat to the safety of miners and property in the coal-mining industries. Because of the higher probability of gas disasters in coal mines, major restrictions are imposed on the simultaneous exploration of coal and gas. Thus, there is a great demand to identify methods for safer, cleaner and more efficient utilization of coal (Wang et al., 2012; Wang and Cheng, 2012; Wu et al., 2011; Wang et al., 2014a, 2014b; Kong et al., 2014; Hungerford et al., 2013; Hao et al., 2014). The coal seams in China are characterized by micro-pores, low permeability, and high adsorption capacity, and these characterizations are reasons for the low efficiency of gas drainage which is an important way to control gas disaster (Xia et al., 2014; Hungerford et al., 2013; Wang et al., 2012; Zhang et al., 2014; Tang et al., 2014).

Recently, hydraulic techniques, characterized by efficient pressure relief and enhancement in permeability and typically represented by hydraulic fracturing and hydraulic slotting, have played an increasingly important role in solving the problem of poor efficiency associated with gas drainage (Gu and Mohanty, 2014; Lu et al., 2010, 2015; Shen et al., 2014; Lin et al., 2014; Zou et al., 2014a, 2014b; Ni et al., 2014). However, limitations such as quick closure of fractures and a limited number of main cracks prevent hydraulic fracturing from being optimal ways to strengthen gas drainage (Zou et al., 2014a, 2014b). In comparison, hydraulic slotting is a better way to improve gas-drainage efficiency by cutting slots in coal seams to form pressure relief space and promote fracture propagation around the borehole, which could be served as potential channels for gas migration (Fig. 1). Because hydraulic slotting is highly efficient at improving gas drainage, extensive research has been carried out to better understand its mechanism for pressure relief and permeability enhancement from macroscopic to microscopic points of view. From a macroscopic perspective, based on the analysis of the mechanism for borehole

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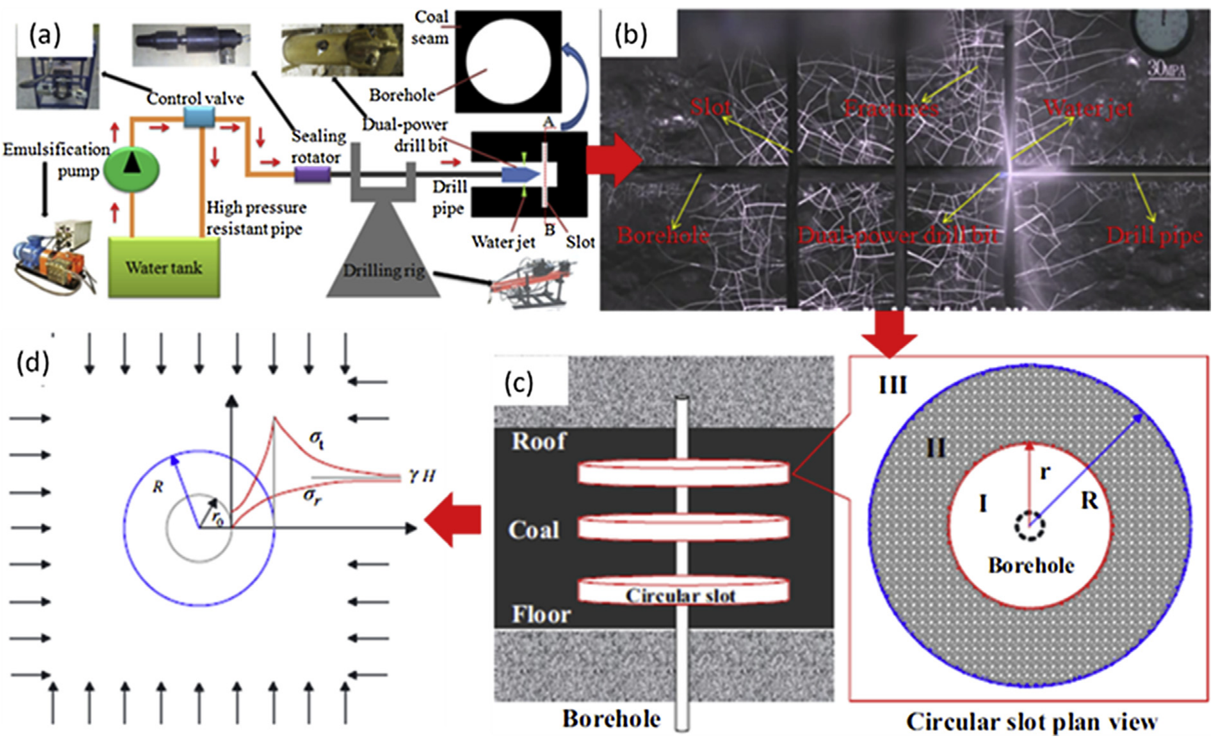

Fig. 1. Schematic of hydraulic slotting: (a) the indigenous hydraulic slotting system and its compositions; (b) slotting process and the slots and fractures around the borehole; (c) three-dimensional diagram of the slots; (d) stress distribution around the slotted borehole.

collapse in soft coal seams, Lu et al. (2010, 2015) proposed a drilling technique using high-pressure pulsed water jet. Results of theoretical analysis and numerical simulation results indicated that this method could improve the porosity and fracture connectivity and thus the permeability of the coal. Yan et al. (2015) reported on a novel ECBM extraction technology based on the integration of hydraulic slotting and hydraulic fracturing. The efficiency of this method was tested and confirmed by field experiments. Shen et al. (2014, 2012a, 2012b) analyzed the relationship between effective stress and the permeability coefficient of coal after water-jet slotting, and conclusions were verified by data obtained from field experiments. Lu et al. (2009, 2011) used the water-jet technique to improve gas-drainage efficiency in high gas content outburst–prone soft coal seams and studied the outburst elimination. Lin et al. (2014) studied the crack-propagation patterns and energy evolution rules of coal within slotting-disturbed zones under various lateral pressure coefficients from a mesoscopic perspective using *PFC^{2D}* software. At the microscopic level, Zou et al. (2014a, 2014b) proposed a method to characterize the pore structure of coal after hydraulic slotting and gas pre-drainage. Using this method, the methane-adsorption property was also investigated.

Based on this analysis, it is obvious that the research efforts thus far have focused on the effect of hydraulic slotting on coal mechanical and seepage behaviors from the perspectives of stress, impact property of water jet, flow characteristics of gas, failure characterization, pore structure, and adsorption properties. However, little attention has been given to the parameters of the slots and their influence on gas-drainage efficiency.

In recent years, much research has been conducted on the failure process and mechanical properties of pre-cracked coal-rock mass, and a large amount of meaningful research results have been achieved with laboratory tests, numerical simulation, and theoretical analysis. In the aspect of physical experiment, Park and Bobet (2009, 2010) conducted extensive experiments on specimens with closed and open flaws. The patterns of crack initiation, propagation, and coalescence were investigated and comparisons were made. Wong and Einstein (2009) characterized the cracks emanating from a single pre-existing flaw by conducting experiments on molded gypsum and carrara marble samples and seven crack types were identified based on the geometry and propagation mechanism. Yin et al. (2014) experimentally investigated the coalescence mechanism between two parallel three-dimensional pre-existing surface cracks in a granite sample under uniaxial compression. The strain fields during the cracking process were captured by the digital speckle correlation method. Haeri et al. (2014) experimentally tested the pre-cracked disk samples under compressive line loading. Yang et al. (2008, 2009) conducted uniaxial and conventional triaxial compression tests on pre-cracked marble. The mechanical parameters and failure process were analyzed systematically for specimens with different flaws. On the numerical simulation, Zhang and Wong (2012, 2013) investigated the crack-propagation process of specimens with single and double flaws by using *PFC^{2D}* software. The parallel-bond forces and displacement fields were also obtained, which revealed some important mechanisms of the cracking processes. Manouchehrian et al. (2014) studied the effect of flaw orientation on the crack-propagation mechanism in brittle materials under uniaxial and biaxial compression. Li and Wong (2012, 2013) investigated the influence of flaw orientation and loading condition on crack initiation and propagation of single-flaw specimen and coalescence of two pre-existing coplanar flaws using *AUTODYN*. Wong et al. (2002) numerically investigated the splitting failure of samples containing pre-existing crack-like flaws under compression using *RFPA^{2D}*. Flaw length, location, and stress interaction between the nearby flaws were found to be important factors affecting the behavior of crack initiation, propagation, and coalescence. Yang et al. (2014a)