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An experimental study of the damage characteristics of gas-containing coal under the conditions of different loading and unloading rates

Minbo Zhang[a,b], Manqing Lin[a,*], Hongqing Zhu[b], Dehong Zhou[a], Longkang Wang[c]

[a] School of Xingfa Mining Engineering, Wuhan Institute of Technology, Wuhan, 430205, China
[b] School of Resource and Safety Engineering, China University of Mining and Technology(Beijing), Beijing, 100083, China
[c] China Center for Information Industry Development, Beijing, 100046, China

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ABSTRACT

The nature of coal and gas outburst involves the gradual damage evolution of gas-containing coal until it becomes suddenly destroyed under the influence of mining. The excavation rate of a working face has an important influence on the mechanical properties of the coal, which are known to be closely related to these disasters. Therefore, based on the mining mechanics path, this study utilized a mechanical testing procedure for gas-containing coal under different loading and unloading rates. Under the conditions of loading axial pressure, and unloading confining pressure (LAUC), the experimental results showed that, when the loading rates of the axial pressure were 0.10 kN/s, 0.14 kN/s, and 0.18 kN/s, the triaxial strength of the coal samples were 37.39 MPa, 39.52 MPa, and 45.68 MPa, respectively, which had increased by 5.7% and 22.2% with the increase in the loading rates. It was observed that the gas flow increased dramatically during the failure stage, and the corresponding increase ranges were more than 4.5 L/min, 1.4 L/min, and 0.3 L/min, respectively. Under the conditions of unloading both the axial and confining pressures at the same time (UAUC), when the unloading rates of the confining pressure were 0.01 MPa/s, 0.02 MPa/s, and 0.05 MPa/s, the coal sample reached a rupture state in a relatively short period of time. Also, the new micro-cracks in the coal samples could not extend or penetrate within a short period of time with the increase in the unloading rates. As a result, the brittle failure of the coal samples were found to be stronger, and the gas flow rates increased to 0.242 L/min, 0.097 L/min, and 0.008 L/min, which indicated that the higher the unloading rate was, the smaller the increase in the gas flow would be. Finally, based on the energy principle, the cumulative dissipation energy was used to define the damage variable of the coal. Then, a damage evolution mathematical model was established on the basis of the logistical equation. It was found that the model could better characterize the damage evolution of the coal, which then provided some theoretical reference values for the prediction of the coal damage. The results of this study potentially provided a design basis for future excavation steps, gas drainage, and outburst prevention measures.

1. Introduction

Coal and gas outburst is considered to be a typical type of coal-rock dynamic disaster. The nature of this disaster is that gas-containing coal gradually experiences damage evolution until it is suddenly destroyed under the influence of mining process (Hu et al., 2008; Yang et al., 2011a,b; Skochinski, 1954; Wierzbicki and Skoczylas, 2014; Ren et al., 2017). Previous studies have demonstrated that when coal which is in a loading state is excavated from an original stress zone, the results are that the stress is loaded into the surrounding rock, causing stress concentration or release. This process potentially causes a series of deformation and damage in the coal. In essence, the above mentioned process has been determined to be one of the most critical causes of coal and gas outburst (Huang and Huang, 2010; Liu and Nie, 2016). However, the loading and unloading rates have an important influence on the mechanical properties of the coal, and are closely related to the excavation steps of the working face. During an actual excavation process in a coal mine, the coal miners often reduce the excavation steps in order to prevent coal and gas outburst. The aim is to adjust the loading and unloading rates of the stress in order to reduce the occurrence of coal and gas outburst accident (He et al., 2017).

In previous related studies (Yin et al., 2013; Qiu et al., 2010; Zhang et al., 2010; Chen et al., 2013, 2014), on the basis of mining stresses, the mechanical characteristics of many types of rock have been extensively investigated by researchers all over the world. The main research results have focused on the following three aspects: First of all,

* Corresponding author.
E-mail address: linmanqing4196@163.com (M. Lin).

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many previous studies have observed the variations in the failure strength and strain by utilizing experimental tests under different mechanics paths. Experimental studies regarding Class II rock under different strain rates were conducted, and an empirical relation theory in which the peak strength increased with the increase in the strain rates was proposed (Okubo et al., 1990; Okubo and Nishimatsu, 1985; Lajtai and Duncan, 1991). Also, the changes in the strength rates of rock have been investigated under different loading and unloading conditions. These studies found that the bearing strength of the rock decreased with the increase in the loading speed of the axial pressure. Furthermore, the bearing strength of the rock increased with the increase in the loading speed of the confining pressure (Yin et al., 2013). In addition, the research conducted by Qiu et al. (2010) analyzed the mechanical properties of deep-buried marble under different unloading confining pressure rates. The results were found to be helpful to increase the understanding of the influence of unloading rates on the mechanical properties of rock. Zhang et al. (2010) studied the rock strength at different unloading rates through experiment testing, the results of which were of great significance for the analysis of rock engineering safety under excavation conditions. Chen et al. (2009) conducted different unloading confining stress rate tests for brittle granite during pre-peak strength and post-peak strength conditions, and explored the entire process of energy accumulation and release in rock failure process on the basis of an energy principle. It was concluded that the faster the unloading rate was, the smaller the maximum strain energy that the rock could store before fracture occurred would be. Secondly, the permeability of rock has also been investigated. Chen et al. (2013, 2014) studied the evolution law of the damage and permeability of coal under the conditions of unloading confining pressure. The conclusions which were drawn from their study have provided great reference values for the safe mining of protective layer. Zhang et al. (2017) examined the damage evolution, along with the post-peak gas permeability characteristics of raw coal under the conditions of loading and unloading. The results provided a new perspective for the study of coal and gas outburst. In addition, a stress-damage-flow coupling model was proposed and applied in coal-bed methane pressure relief in deep coal seams (Yang et al., 2011a,b). Thirdly, the damage process has been monitored by different physical tests, such as CT, acoustic emission, electromagnetic radiation, and so on. Liu et al. (2012) conducted a CT real-time experiment to study the creep damage evolution process of coal under the conditions of compression, and the results revealed the dynamic disaster process of coal. Also, the acoustic emission tests have been used to monitor the damage process of coal, and have provided reference values for the study of the precursor information before failure (Yang et al., 2015; Kong et al., 2017). In addition, Song et al. (2012) investigated the relationship between electromagnetic radiation energy and the damage to loaded coal by taking the hysteresis loop as a bridge produced during the loading and unloading process.

Previously, great progress has been made regarding the mechanical properties, permeability, and damage monitoring of rock under different mechanics paths. However, there has been few research studies conducted on the damage evolution of gas-containing coal under different loading and unloading rates, especially in the case where both the axial pressure and confining pressure unload simultaneously. In addition, coal is a typical example of a highly heterogeneous material, which contains complex mineral materials linked by a large number of different sized pores and cracks (Ndaji et al., 1997; Mathews and Chaffee, 2012; Song et al., 2017). Therefore, the damage and deformation of gas-containing coal under the influence of mining activities are extremely complex nonlinear process. Previously, it has been impossible to accurately establish the failure criterion by relying on the traditional classical elastic-plastic mechanics. However, the damage evolution process of gas-containing coal can be obtained based on the principle of energy, and a mathematical model of the damage evolution can then be established.

In this research study, FLAC3D is used to analyze the change

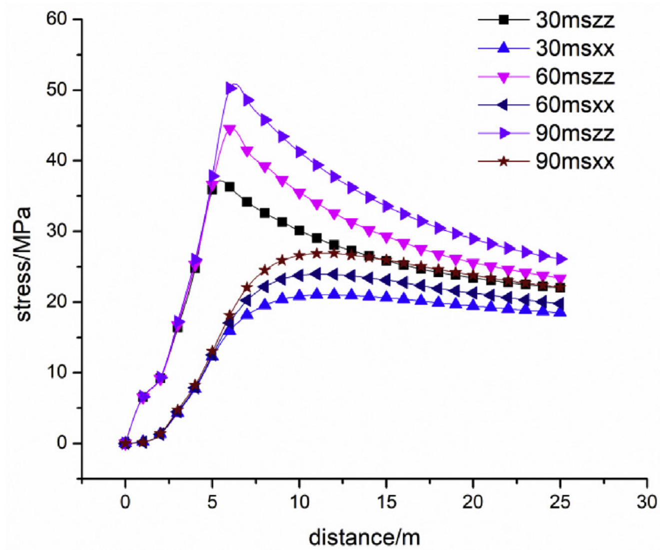

Fig. 1. The stress distribution of different mining distance.

relationship between vertical stress (SZZ) and strike stress (SXX) during the exploration of the #2 coal seam in the Dashucun Mine, at the distance of 30 m, 60 m and 90 m, in order to determine the mechanical path of the experiment. The stress distributions of different mining distance are shown in Fig. 1. With the maximum of vertical stress as the dividing point, there are two typical mechanical paths in front of the working face. One is the strike stress declining in the increasing process of the vertical stress, and the other is the simultaneous declining of the vertical stress and strike stress. Based on the above analysis, in combination with the characteristics of a mechanical experimental machine, two types of experimental research were performed. The first involved the loading of the axial pressure, and the unloading of the confining pressure (LAUC). The second involved the unloading of both the axial pressure and the confining pressure at the same time (UAUC). Based on the experimental results, the principle of the energy was used to investigate the damage evolution of the coal, and a mathematical model of the damage evolution was established by means of the logistical equation.

2. Experimental method

2.1. Samples preparation

The coal samples used in this experiment were taken from the #18 coal seam of the Nanshan Mine, which was located in China's Hegang coalfield. The mining depth was 550 m, and the gas pressure was 0.89 MPa. In addition, the permeability was low, and a severe risk of coal and gas outburst was present. Large coal samples were selected from the working face, which were sealed and transported to the research laboratory for cutting, drilling, and grinding. Finally, they were processed into standard sizes with a diameter of 50 mm and length of 100 mm. The coal samples were screened in order to reduce the discreteness of the test results. First, the coal samples with no obvious scarring on the surface were selected through observation. Second, through testing the wave velocity of sound passing through the samples, the coal samples with similar wave velocity were selected to carry out the mechanical experiment. The sound wave testing device is shown in Fig. 2, and the measurement results of the sound wave are shown in Table 1. This experimental device can be used to measure the acoustic wave velocity through coal body under different conditions, and consists of a force loading system, acoustic measurement on its elastic cavity body, acoustic emission system, and data acquisition system. The force loading system can realize two different loading methods, i.e.