Journal of Applied Geophysics 124 (2016) 139–147

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Fractal characteristics and acoustic emission of coal containing methane in triaxial compression failure

Xiangguo Kong [a,b], Enyuan Wang [a,b,*], Shaobin Hu [c], Rongxi Shen [a,b], Xuelong Li [a,b], Tangqi Zhan [a,b]

[a] Key Laboratory of Coal Mine Gas and Fire Prevention and Control of the Ministry of Education, China University of Mining and Technology, Xu Zhou, Jiangsu 221116, China
[b] School of Safety Engineering, China University of Mining and Technology, Xu Zhou, Jiangsu 221116, China
[c] Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430000, China

ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form 16 November 2015
Accepted 29 November 2015
Available online 30 November 2015

Keywords:
Acoustic emission
Fractal characteristics
Correlation dimension
Gas
Pores and cracks

ABSTRACT

Aimed at exploring the influence of methane to coal and studying fractal characteristics and acoustic emission (AE) features in the damage evolution, the triaxial compression experiments of coal containing methane were conducted, and acoustic emission response was collected simultaneously in the loading process. Based on the method for calculating the correlation dimension, the fractal dimension was calculated with regard to time series of acoustic emission. Our experimental results indicate that AE response and fractal dimension can reflect the evolution and propagation of cracks in the loading process. Corresponding to the load–time, acoustic emission experiences active, linearly increasing, rapidly augmenting and decreasing stage. However, the fractal dimension of AE develops from chaos to orderly state. Late loading, a continued slowdown in fractal dimension, can be used as a precursory signal of coal sample destruction. In addition, the amount of gas in the coal sample will influence the evolution of pore and fracture, which causes a variation in the acoustic emission signals and fractal dimension. The maximum bearing load reduces 18.85% and 49.18% within pore pressure of 0.75 and 1.5 MPa, compared with it (24.4 kN) of the coal sample (without gas). What's more, the increase of pore pressure will cause the growth of AE count and energy, but the correlation dimension of AE parameters drops. This study is helpful for us to understand the effects of methane to coal and the evolution mechanism of cracks, and it can be applied to the research on occurrence mechanism and early warning of coal and gas outburst.

1. Introduction

With the increasing depletion of shallow resources, coal mining has entered the deep mining stage. With sharp increase in stress and gas pressure, dynamic disasters of coal and gas will become more frequent and serious, which severely pose a threat not only to the miners but also to the production safety (Hu et al., 2014; Wang et al., 2012; Gonzatti et al., 2014). During the deformation and damage process of coal and rock materials, the strain energy is released in the form of elastic wave, which quickly spreads in the solid materials, such as coal and rock, subsequently producing acoustic emission (AE) phenomenon (Yang et al., 2014; Meng et al., 2014). The AE signals generated contain a wealth of information about the loading process. If the AE signals are analyzed in-depth, information about the internal structural changes and failure mechanism of coal or rock specimens can be obtained. This can then subsequently be used to provide a theoretical basis for monitoring and forecasting dynamic disasters of coal or rock bearing gas.

* Corresponding author at: Key Laboratory of Coal Mine Gas and Fire Prevention and Control of the Ministry of Education, China University of Mining and Technology, Xu Zhou, Jiangsu 221116, China.
E-mail addresses: kxgtudou7218@163.com (X. Kong), weytop@263.net (E. Wang).

Many scholars have carried out studies on AE characteristics during the deformation and damage process of coal and rock. Since Obert (1941) and Hodgson (1942) proposed the concept of AE and Kaiser (1953) discovered the Kaiser effect of acoustic emission, AE technology has successfully been applied to managing and preventing coal mine disasters, even 70 years after its development (Cao et al., 2007; Shkuratnik et al., 2004, 2005; Liu et al., 2007). Cao et al. (2007) studied the characteristics of acoustic emission in coal outbursts, and concluded that the ringdown-event ratio is related to the change of energy in the coal specimen. This method can thus be used to predict dynamic disasters in coal mines. Shkuratnik et al. (2004, 2005) systematically studied the acoustic emission behavior characteristics of coal and rock under uniaxial and triaxial loading experiments. Fu (2005); Zhao et al. (2014); Zhao et al. (2015); Liu et al. (2015) and Liu et al. (2007) analyzed the deformation characteristics and acoustic emission rules of coal and rock samples. For the entire period of uniaxial compression of sandstone, the changes in electrical resistivity and AE response characteristic with damage evolution were studied by Li et al. (2014a), and their results showed that these two parameters can be used to predict the damage evolution of sandstone during the loading process. To truly simulate the underground (coal mine) stress environment, triaxial experiments have been performed by several scholars (Chen, 2008; Su et al., 2006). Chen (2008) analyzed the effects of confining pressure on AE characteristics.

http://dx.doi.org/10.1016/j.jappgeo.2015.11.018
0926-9851/

Su et al. (2006) considered that the acoustic emission characteristics were related to loading mode during the triaxial failure process of coal. In actual mining conditions, the coal in the working face will experience stress concentration and unloading repeatedly. He et al. (2014) studied acoustic emission characteristics of coal specimen under triaxial cyclic loading and unloading conditions, and reported that AE information is obtained in the interval of cyclic loading and unloading processes. In addition, they noted that the changes in the energy count and amplitude are the same and these changes coincide with the stress experienced by coal specimens. Under uniaxial compression, Wang (1997), Wang et al. (2004) studied the effects of acoustic emission and the spectrum features, and reported that acoustic emission characteristics can reflect the degree of internal damage in coal and rock, which is directly related to the internal defect and damage evolution.

The aforementioned studies were mainly related to the acoustic emission responses in the failure process of coal and rock without gas. However, in actual coalmining conditions, methane plays a pivotal role in the evolution of dynamic disasters. This is supported by the fact that several studies (e.g., Ni et al., 2014; Qin et al., 2013; Majewska and Mortimer, 2006; Majewska and Ziętek, 2007; Xue et al., 2013) have suggested that the amount of methane in coal or rock specimens will affect the mechanical properties and microstructure of coal. The process of gas adsorption causes swelling deformation and desorption produces shrinkage deformation (He et al., 1996; Liu et al., 2010; Cao et al., 2013; Ni et al., 2014; Zou et al., 2014); in addition, the strength and elastic modulus of coal decrease due to gas adsorption. Milewska-Duda et al. (1994, 2000) compared the theoretical and empirical expansion of coal during the process of high-pressure adsorption of methane, and studied the adsorption of methane and carbon dioxide in hard coal and active carbon. Majewska and Mortimer (2006) and Majewska and Ziętek, 2007) discussed the chaotic behavior of acoustic emission induced in hard coal by gas adsorption–desorption. Ma et al. (2012a, 2012b) conducted methane adsorption and seepage experiments, and found that the AE characteristics are active in the initial stage of adsorption, and that the AE was paroxysmal in time domain. Meng et al. (2014) investigated acoustic emission characteristics in failure process of coal under conditions of fixed confining pressure and different gas pressures. They concluded that an exponential decay relationship exists between the gas pressure and acoustic emission. Qin et al. (2013) also studied the acoustic emission characteristics of coal and rock under different gas pressures. They established and verified the relationship between AE count and damage in coal and rock structures under different gas pressures. Kong et al. (2015) analyzed critical slowing down of acoustic emission and found that variances and autocorrelation coefficients of AE counts to time sequences increase before the failure of coal. Studies on acoustic emission characteristics in the loading of coal can help us understand the internal defects and damage evolution of coal and rock to some extent.

Mandelbrot (1977) proposed fractal theory in the mid-1970s. Xie (1996) successfully combined damage mechanics and fractal geometry in 1991, creating a new field about rock fractal theory research. At present, the rock fractal theory research field has made a series of achievements (Xie et al., 2003; Xu and Xie, 2004; Wang and Gao, 2007; Sun and Xie, 2008; Li et al., 2010). In terms of AE generated during the formation and expansion of cracks, Biancolinia et al. (2006) presented a good description about the evolution process of the rock cracks by box fractal dimension. Kusunose et al. (1991) discussed fractal dimension of spatial distribution of granodiorites, and concluded that the texture of rock may affect the expansion of microcracks inside and distribution of AE events. Voznesenskii and Tavostin (2005) studied AE characteristics before the peak phase of coal destruction and analyzed accumulative AE counts at the different regions. The authors obtained correlation coefficients of accumulative AE counts at the different regions as a constant in the prepeak stage. Gao et al. (2013a, 2013b, 2014) studied acoustic emission and fractal characteristics of coal under uniaxial and triaxial compression, and concluded that AE and fractal characteristics behave differently under different confining pressures. Fractal and chaos characteristics of acoustic emission were studied in the whole process of stress–strain by Jiang et al. (2010), and the evolution of cracks was described using logistic equation. Li et al. (2014b) built the nonlinear relation between fractal dimension and displacement at the top by studying the fractal characteristics of heterogeneity rock specimens subjected to uniaxial compression test. Wu et al. (2012) and Yin et al. (2005) proposed that the continuous decline of AE fractal dimension can act as a precursor of rock destruction. Li et al. (2009) found that the fractal dimension of acoustic emission and b values are similar in loading process. Therefore, in the actual application, these two parameters can be combined to monitor rock stability.

Thus, from the aforementioned studies it is obvious that fractal theory had great potential to explain microscopic fracture of coal or rock specimens. However, the role of gas in microcosmic rupture of coal remains to be studied completely. In this paper, we carried out triaxial rupture tests of coal containing gas within equivalent confining pressure conditions. Based on the fractal theory, the fractal dimension values of AE time series were calculated, which further revealed the microscopic fracture mechanism of coal containing gas. In accordance with the details obtained, we analyzed the effect of methane on physical properties of coal, acoustic emission responses, and fractal dimension. Our study result showed that fractal dimension decreases continuously with time, and thus has the potential to act as precursor of coal failure.

2. Acoustic emission test of coal containing gas under triaxial compression

2.1. Experiment system

The experimental system consists of an axial loading subsystem, a confining pressure loading subsystem, an acoustic emission monitoring subsystem, a vacuum pump, a gas bottle, and a pressure cylinder. Fig. 1 shows this experimental system.

(1) The axial loading subsystem is an electrohydraulic servo pressure testing machine controlled by a microcomputer (YAW4306), which can achieve displacement loading and stress loading and record the displacement, load, and time during the loading process. In addition, it can also perform uniaxial pressing, stretching, cyclic loading, and creep experiments.
(2) The confining pressure loading subsystem consists of a nitrogen cylinder, charge and discharge pipes, valves, and pressure gauge. When the valve of nitrogen cylinder is opened, the cylinder would be filled with nitrogen, with a certain pressure, to realize the uniform confining pressure loading.
(3) The acoustic emission monitoring system used was CTA-1 acoustic emission data-acquisition system (American Physical Acoustics Co). It performs a series of functions such as the parameter setting, signal acquisition, signal A/D conversion, data storage and graphic display, waveform acquisition, and spectral analysis. In this experiment, the sampling frequency was set as 500 kHz and the threshold value as 46 dB.
(4) The middle portion of the top cover of the pressure cylinder with the rigid structure is the loading rod, whose bottom diameter is larger than that of the samples, enabling complete contact with the coal sample. Gas used in the experiment was of high purity (99.99%).

2.2. Sample characteristics and preparation

Coal samples were collected from the Si Jiazhuang colliery, located in Xiyang county of Shanxi Province, China and affiliated with Yangquan Coal Industry (Group) Co., Ltd. The coal seams #8, #9 and #15 are the most mineable in Si Jiazhuang colliery. The absolute gas pressure and