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Critical slowing down on acoustic emission characteristics of coal containing methane

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The behavior of coal containing methane under triaxial compression with equivalent confining pressure was evaluated using YAW4306 microcomputer-controlled electrohydraulic servo stress testing machine and CTA-1 acoustic emission collecting system. In addition, stress strain and AE signals were monitored simultaneously during the loading process. The critical slowing down theory was introduced to analyze variances and autocorrelation coefficients of AE signal sequences. Experimental results indicate that because of the presence of methane, the compressive strength and elastic modulus of coal decrease with increases in pore pressure. During the failure of coal containing methane under equivalent confining pressure, acoustic emission response with time experiences compaction change, stable growth, accelerated growth, and remission, and a corresponding stress–strain curve is obtained. Adsorption swelling deformation and free gas expansion of the coal samples activate AE signals in the compaction change stage. Under triaxial compression with different confining pressure and pore pressure, the AE characteristics of coal samples exist phenomenon of critical slowing down. Variances and autocorrelation coefficients of AE counts to time sequences, increase before the failure of coal, and therefore, variances and autocorrelation coefficients can act as precursor signals of failure of coal. Compared with mutation points of AE accumulative signals as precursory signals, the time lag between the precursory signals and mutation point shorten, which accounts for 2–10% of the total loading time, in a reasonable range.

1. Introduction

Because of increased hazards, strong burst, and underlying complex mechanisms, the dynamic disaster of coal containing gas is considered the most serious disaster in coal mines. With the increase of mining depth and intensity, dynamic disaster of coal containing gas will seriously threaten the safety production of coal mines (Meng et al., 2014). During the process of breeding, that is, formation and development of dynamic disaster of coal containing gas, the structure of coal body changes and cracks are formed, which extend uniformly, eventually leading to the macroscopic fracture. The effect of gas in this process cannot be ignored. Adsorption of methane will produce swelling deformation and desorption with shrinkage deformation (Ceglarska-Stefańska et al., 1993, 2001; Busch et al., 2004, 2006; Cui et al., 2007; Bustin et al., 2008; Day et al., 2008), which will weaken resistance to deformation, thereby promoting dynamic disasters to happen. During the compression failure process of coal samples, cracks closing and slipping, microcracks developing and linking, which will lead to deformation and macrofracture (Su et al., 2009; He et al., 2010; Ma et al., 2012a,b; Yin et al., 2012; Majewska et al., 2013; Wasantha et al., 2014; Yang et al., 2014; Ganne et al., 2007; Lemaitre, 1984), all of these activities will cause acoustic emission. Therefore, capturing and analyzing acoustic emission signals is of great importance to study the precursory signals and the mechanism underlying coal and rock cracking.

Many studies were carried out and valuable results were obtained with regard to the acoustic emission characteristics and

Abbreviations: AE, acoustic emission; sjz, Shi Jiazhuang; CVP, the compaction variation period; SGP, the steady growth period; AGP, the accelerating growth period; MP, the moderate period; CS, the compaction stage; ES, the elastic stage; YS & DS, the yield and damage stage; RS, the residual stress stage.

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precursory signal analysis of loading process. Obert and Duvall (1941) monitored the location of crack, which was caused by excavation, in coal and rock using acoustic emission equipment and determined the maximum stress area. Shkuratnik et al. (2004, 2005) systematically studied the acoustic emission behavior characteristics of coal and rock under uniaxial and triaxial loading experiments. Under the uniaxial compression condition, the acoustic emission characteristics of rock specimen (Li et al., 2004; Zhang et al., 2006; Jin et al., 2013; Knill et al., 1968), deformation analysis and acoustic emission rules of coal and rock (Fu et al., 2005; Cao et al., 2007; Liu et al., 2007; Majewska et al., 2007a,b, 2008; Pone et al., 2010), and damage evolution and acoustic emission characteristics (Woo et al., 2014; Li et al., 2014; Chen et al., 2013) were systematically studied. Su et al. (2006), Chen et al. (2008) and Ai et al. (2011) studied the acoustic emission characteristics during the failure process of coal and rock under the triaxial condition. He et al. (2014) studied acoustic emission characteristics of coal specimen under triaxial cyclic loading and unloading. Wang (1997, 2004) studied the effects of acoustic emission and the spectrum features in the failure process under uniaxial compression, and suggested that acoustic emission can reflect the degree of internal damage of coal and rock, which is directly related to the internal defect and damage evolution. These previous studies mainly focused on the acoustic emission in the failure process of coal and rock without gas.

However, the gas in coal and rock has played a very vital role in coal and rock dynamic disasters. Therefore, the influence of gas on acoustic emission of coal and rock cannot be ignored (Markham et al., 1931; Greaves et al., 1993; Milewska-Duda et al., 1994, 2000; Majewska et al., 2006, 2007a; Fitzgerald et al., 2005). Many studies (He et al., 1996; Liu et al., 2010; Cao et al., 2013; Zhang et al., 2014; Ni et al., 2014) have suggested that gas adsorption produces swelling deformation and desorption produces shrinkage deformation. The strength and elastic modulus of coal containing gas decrease due to the gas adsorption. Therefore, while studying the characteristics of acoustic emission during the process of coal containing gas burst, the effect of the gas should be considered. Meng et al. (2014), under conditions of fixed confining pressure and different gas pressures, studied the failure of coal containing gas and concluded that the gas pressure and acoustic emission cumulant shows an exponential decay relationship. Yin et al. (2013), Mazumder et al. (2008), Wang et al. (2010), Ding et al. (1990), and Li et al. (2009) studied the seepage features and the acoustic emission characteristics of coal and rock containing gas under different stress paths. The authors reported for that the acoustic emission of coal and rock containing gas has different amplitude curves under different stress paths. The acoustic emission appears as a double-humped state from the starting point of the unloading confining pressure under the path of unloading confining pressure. Qin et al. (2013) studied the acoustic emission characteristics of coal and rock under different gas pressures. They established and verified the relationship between AE count and damage of coal and rock under different gas pressures. Ma et al. (2012) studied the AE characteristics of gas adsorption filtration in coal, and found that the AE characteristics are active in the initial stage of adsorption, and that the AE was paroxysmal in time domain. Liu et al. (2012) applied fractal theory to discuss evolution of AE sequences in the fracture process of coal containing gas. Their study results show that the gas had a significant impact on the acoustic emission characteristics of coal burst. However, existing studies mainly focus on the acoustic emission rules in the process of coal and rock burst. The internal changes of AE response with time sequences have rarely been studied. Thus, processing the AE signals and analyzing its the internal changes characteristics are considered significant to illustrate the underlying rupture mechanism and study abrupt signals of coal sample.

Many studies (Meng et al., 2014; He et al., 2014; Yin et al., 2013; Yang et al., 2014) have reported several important achievements with regard to the evolution of AE behavior during the process of coal and rock loading, which have played a vital role in understanding the conditions that trigger coal and rock burst as well its underlying mechanisms. However, to date, very few studies have reported on the acoustic emission response during failure of coal under equivalent confining pressure. In addition, even fewer studies have processed acoustic emission signals based on the theory of critical slowing down. This paper focuses on triaxial loading damage, stress, strain under the equivalent confining pressure and acoustic emission signal response over time. The theory of critical slowing down is also introduced (Bak et al., 1989; Oodano et al., 1993; Venegas et al., 2005; Koide, 2005; Dakos et al., 2008; Scheffer et al., 2009; Ramos, 2010; Yan et al., 2011; Wu et al., 2013; Gao et al., 2013), which be applied for studying climate mutation and earthquake precursors. With regard to acoustic emission signal during failure of coal sample under equivalent confining pressure, the phenomenon of critical slowing down reveals that the acoustic emission count variance and the autocorrelation coefficient can be used as precursory indicators, which could indicate rupture of coal sample.

2. Experimental analysis

2.1. Characteristics of the study samples

The original coal sample was collected from the Si Jiazhuang coalmine, and made into coal briquettes to reduce the impact of inhomogeneity fracture distribution on the test results and to increase the comparability of the experiment. The coal is crushed and filtered through a 40-mesh sieve, after which it is molded under a high stress load (250 kN). This stress load was maintained for 6 h, and the coal is processed into standard cylindrical samples (diameter, 50 mm; length, 100 mm). Fig. 1 shows the coal samples thus prepared.

2.2. Experiment system

The experimental system consists of an axial loading subsystem, a confining pressure loading subsystem, acoustic emission monitoring subsystem, vacuum pump, gas bottle, and the pressure cylinder. Fig. 2 shows this experimental system. 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. The confining pressure loading subsystem consists of a nitrogen cylinder, charge and discharge pipes, valves, and pressure gauge. The acoustic emission monitoring system used was CTA-1 acoustic emission

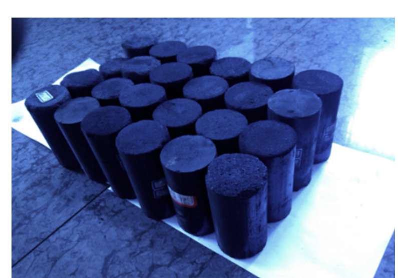

Fig. 1. Picture of coal samples.