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Acoustic emission signals frequency-amplitude characteristics of sandstone after thermal treated under uniaxial compression

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A B S T R A C T

Thermally treated sandstone deformation and fracture produced abundant acoustic emission (AE) signals. The AE signals waveform contained plentiful precursor information of sandstone deformation and fracture behavior. In this paper, uniaxial compression tests of sandstone after different temperature treatments were conducted, the frequency-amplitude characteristics of AE signals were studied, and the main frequency distribution at different stress level was analyzed. The AE signals frequency-amplitude characteristics had great difference after different high temperature treatment. Significant differences existed of the main frequency distribution of AE signals during thermal treated sandstone deformation and fracture. The main frequency band of the largest waveforms proportion was not unchanged after different high temperature treatments. High temperature caused thermal damage to the sandstone, and sandstone deformation and fracture was obvious than the room temperature. The number of AE signals was larger than the room temperature during the initial loading stage. The low frequency AE signals had bigger proportion when the stress was 0.1, and the maximum value of the low frequency amplitude was larger than high frequency signals. With the increase of stress, the low and high frequency AE signals were gradually increase, which indicated that different scales ruptures were broken in sandstone. After high temperature treatment, the number of high frequency AE signals was significantly bigger than the low frequency AE signals during the latter loading stage, this indicates that the small scale rupture rate of recurrence and frequency were more than large scale rupture. The AE ratio reached the maximum during the sandstone instability failure period, and large scale rupture was dominated in the failure process. AE amplitude increase as the loading increases, the deformation and fracture of sandstone was increased gradually. By comparison, the value of the low frequency amplitude was bigger than the high frequency amplitude on the whole.

1. Introduction

With the increase of the world's energy demand and the increasing strength of coal mining, shallow resources gradually decreased, the domestic and foreign mines have entered the state of deep resource exploitation (He et al., 2005; He et al., 2010; Xie et al., 2015). With the increasing of mining depth, the underground engineering need to face more increasing disasters such as the increasing frequency and intensity of coal dynamic disasters, the large deformation of roadway in surrounding rock, the rheology and the underground temperature rise (Sellers et al., 2000; He et al., 2010; Xie et al., 2015). Therefore, the problems of mechanics behavior in rock deformation and fracture have become a focus research at domestic and overseas. Deep underground engineering, such as the selection of nuclear waste storage sites (Chen et al., 2015), need to consider the influence of temperature on rock mechanical properties. In addition, the overlying strata were usually covered by the sandstone, when the sandstone under high temperature treatment or fire baking (Kuenzer et al., 2012), the sandstone internal structure changed (Hajpál, 2002), which affected the stability of the overlying strata. Therefore, it is significant to study thermally treated rock deformation and fracture behavior, meanwhile, it has great significance to evaluate the thermal stability of underground engineering and coal mine fire detection.

Rock as a kind of natural non-homogeneous material, there existed varying degrees defects including micro cracks between particles (cracks) and joints (He et al., 2005; He et al., 2010). The process of rock failure and internal micro crack evolution process was consistent, the cracks expansion and fracture of the rock caused stress relaxation, part of the energy stored in the rock were suddenly released thus produced AE signals (Gong et al., 2013). AE detection technique was a very effective non-destructive technique applied to identify micro and macro-defects and their temporal evolution in several materials, such as rock (Read et al., 1995), coal (Wang et al., 2004; Lu et al., 2012), masonry structures (Masera et al., 2011). AE was a kind of elastic wave, the

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wave intensity as well as frequency component contained rock failure and mechanism information, the study of AE signals can be infer the changes of rock internal state and reveal the rock failure mechanism (He et al., 2010; Hou et al., 2016).

AE phenomenon can be produced in the process of the deformation and fracture of rock during the high temperature environment (Chmel et al., 2014; Chen et al., 2014), the amplitude-frequency response of the AE time series showed the presence of a few populations of cracks differing in size in the range 0.25 mm to 2.3 mm (Chmel et al., 2015). When the temperature was above 500 °C, more AE signals appeared before the peak during the rock deformation and fracture, beyond 600 °C treatment, the phase transformation appeared in the internal structure of the rock, AE signals changed significantly when sandstone happened to instability failure. AE signals could well reflect the internal crack development and the evolution process of thermally treated sandstone, between the initial damage to the final damage, the higher the temperature, the stronger the AE activities was (Kong et al., 2016a), the AE signals increased with great rapidity around the peak stress, the AE energy was great increased during the instability failure stage (Li et al., 2014).

AE signals processing methods can be divided into the parameter analysis method and the waveform analysis method (Ji et al., 2012; Duan et al., 2015). The detected AE signals may result from different sources, e.g. plate friction, crack closure, and crack growth, etc. Statistical characteristic parameters indicated the stress condition during the particle fragmentation (Mao et al., 2015; Agioutantis et al., 2016). Rock failure was a multi-scale and nonlinear dynamic process. Many researchers have conducted the AE characteristics analysis for source mode identification (Giordano et al., 1998; Ni et al., 2002). AE waveform analysis method was mainly the Fourier analysis method (He et al., 2010), based on the Fourier analysis method, AE signals was transformed from the time domain to the frequency domain.

The dominant frequency of the AE event was used as the defining parameter for AE signals differentiation (Groot et al., 1995). Cai et al. pointed out that the high frequency AE signals was corresponding to the small scale crack, the low frequency AE signals was corresponding to the large scale crack (Cai et al., 2007). High-amplitude AEs can be generated in Inada granite micro-cracking,the ratio of the AEs increased as the amplitude increases (Yoshida et al., 2004). Low frequency AE signals increased when granite rocks close to the instability failure under the uniaxial compression test (Ohnaka et al., 1982). Under true-triaxial condition, AE signals was existed two main frequency ranges, i.e. lower (60–100 kHz), and higher (170–190 kHz) (He et al., 2010). Water saturated sandstone under the three axis compression shown that high frequency and low amplitude were emerged before the peak value, the low frequency and high amplitude emerged after the peak value (Read et al., 1995). The AE test of rock under hydraulic coupling shown that the AE frequency was related to the strength of the rock, the higher the intensity, the wider the main frequency distribution, the main frequency distribution of the AE signals was changed wider at the failure stages (Li et al., 2006). The dominant frequency distributions of the silica and coral sand showed that high frequency components were mostly observed when the stress level was high (Mao and Towhata, 2015). Through the uniaxial compressive test, AE signals frequency spectrum was not static, but changed with the loading and failure process, basically with the increase of loading and deformation failure process enhanced, the dominant frequency increased (Wang et al., 2004).

Under the loading process, different frequency components corresponding to the different types of AE sources. Different frequency of AE signals corresponded to the microscopic damage in different types of rock. Therefore, the stage characteristics of AE waveforms and the development characteristics of frequency spectrum can reflect the information of rock damage and rock loading state, which provide a basis for the prediction of rock stability. In this paper, through the uniaxial compression experiments of sandstone after different temperature treatment, the frequency spectrum characteristics and the change rules of AE signals waveforms during the deformation and fracture of sandstone under room temperature and after high temperature treatment were studied, the precursor information of deformation and fracture of sandstone after different temperature treatment were comprehensive analyzed.

2. AE test experiments under uniaxial compression

Uniaxial compression experiments of sandstone were carried out in this section, the new SANS microcomputer electro-hydraulic servo pressure testing machine was used as the loading system. The stress, strain, loading time can be collected synchronous during the whole loading process. The AE acquisition and control system was DISP series Test for Express Rock - 8 full digital 24 channels AE acquisition and control system (the United States Physical Acoustics company), the system had the full waveform acquisition processing function and real-time three-dimensional positioning.

The experimental samples were taken from Shanxi, China, the contents of minerals were shown in Table 1 by X-ray diffraction test analysis. The sandstone samples were prepared as cylindrical samples with Φ50 mm × 100 mm, the production and selection process were strictly according to the standards of the International Society for Rock Mechanics (ISRM). The selected samples were divided into 6 groups, each group including 5 samples. The QSH-1200T box type high temperature furnace was used to heat the samples, and the samples were heated from room temperature to 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C, after constant heat the samples for 2 h, then cooling down. AE signals were collected with the same conditions of each specimen under uniaxial compression tests. The testing machine adopt force controlled loading method, the loading rate was set to 200 N/S.

AE signals were received by the NANO-30 transducers. The NANO-30 transducer has the advantage of high sensitivity and high signal noise ratio, the resonance frequency of the NANO-30 transducers is 140 kHz, the frequency range is 0-400 kHz. The peak frequency of the transducer is 283.2 kHz. The transducer was coupled on sandstone samples with the vaseline, at the same time, the AE signals' waveforms were obtained during the collected process. The received analog signals were transferred to the digital signals through the high speed data acquisition system, the threshold value of the AE instrument was set to 40 dB, the lower limit of the filter parameters was set to 1 kHz, the upper limit was 400 kHz, a total of 1024 data were collected in every incident event, the acquisition rate was 1 MHz. When the AE intensity exceeding the preset threshold value, the high speed data acquisition system recording a total of 1024 data for a collision (each collision may contain one or several AE events) around this trigger point center.

Experimental system was shown in Fig. 1, the system mainly concluded the loading system (including press 1 and sample 3), the AE signals data acquisition system (contains the AE signals sensor 4 and high-speed data acquisition system 6), the load and displacement records system (including load sensor, resistance strain and displacement gauge, displacement transducer and recorder).

3. Experimental result

After high temperature treatment, sandstone mechanical properties changed obviously, high temperature caused thermal damage to sandstone, sandstone strength decrease gradually, the strain increased obviously, sandstone brittleness was abate, and ductility increase gradually. The stress strain curve was shown in Fig. 2, the stress strain curve to a great degree reflect the deformation and failure process of sandstone.

Table 1
Contents of minerals.

Mineral	Quartz	Potassium feldspar	Dolomite	Siderite	Clay mineral
Content (%)	53.7	18.5	4.6	4.1	18.1