Experimental study on resistivity and electromagnetic radiation of coal under uniaxial compression

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In order to study the response of resistivity and electromagnetic radiation at different stages of deformation and failure of loaded coal, the real-time measurement system of acoustic emission, electrical parameters and electromagnetic radiation of loaded coal was established, the variation characteristics of resistivity and electromagnetic radiation pulse were tested respectively in the vertical bedding direction of different coal under uniaxial loading, and the variation regularity was discussed. The research results indicate that in the initial compaction stage, the electromagnetic radiation pulse increases and the resistivity fluctuates to a certain extent with the closure of coal pores and fissures. In the elastic stage, the EME (Electromagnetic Effects) pulses and change of resistivity decrease greatly and the change curve of resistivity is close to be linear. In the unstable development stage, the EME pulses show the peak value, the resistivity fluctuates obviously and tends to decrease further before the stress peak. Through the comparative analysis of resistivity and electromagnetic radiation pulse, the increasing area of electromagnetic radiation pulse generally appears in the area with the large changes of resistivity.

Keywords: resistivity; electromagnetic radiation; uniaxial compression; coal.

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1. Introduction

The fracture process of coal or rock under loading condition is often accompanied with the physical phenomena such as acoustic emission and electromagnetic radiation [1–4]. The electromagnetic radiation is also an important physical phenomenon during the breeding and development of coal and rock dynamic disasters in mines. The resistivity is not only an important physical property parameter of coal and rock materials, but also the main parameter to study the electromagnetic radiation propagation of coal and rock. The significant difference of resistivity can cause the spatial and temporal distribution changes of electromagnetic radiation propagation [5].

For the static resistivity test of coal and rock, these researchers such as brach [6], Dindi [7] and Lei [8] conducted the relevant research from the aspects of temperature, frequency and dispersion. Ryu et al. [9] measured the resistivity of jointed rock samples and found that the electrical resistivity wass affected by the location, size, and the characteristics of jointed rockmasses. Brace and Orange [10] studied the change characteristics of resistivity by the bipolar method during the deformation and fracture of rock. It was found that the resistivity showed an increase-steady-decrease trend with the increase of stress. Chen and Lin [11] carried out the resistivity experiments on marble, limestone and other rocks under uniaxial compression, obtained the variation curves of resistivity and stress-strain in each stage, and fitted the corresponding empirical formulas for three parameters in each stage.

Dayuan et al. [12] tested the resistivity of granite with different saturation under uniaxial stress loading. It was found that the resistivity would increase - stabilize - decrease with the increasing stress. Before the main fracture of rock, the resistivity would have a negative abnormal amplitude caused by "stress repetition". Chen et al. [13] conducted a large number of resistivity experiments on rock materials under uniaxial and confining pressure . They not only studied the change relationship of resistivity with stress, but also studied the dynamic relationship between the main fracture direction and the change direction of resistivity, and put forward the determination method of main fracture direction by the resistivity.

Based on the U1733C LCR test instrument, Enyuan et al. [14] carried out the resistivity experiments on different coal samples and also studied the regularity between the stress-strain and resistivity under uniaxial and cyclic loading. Based on the HIOKI 3532-50 LCR test instrument, Li et al. [15] experimentally measured the resistivity of gas bearing coal under triaxial loading and studied the effects of stress, gas, temperature and moisture on the resistivity of different coal.

From the above studies, it can be seen that the previous experience and empirical researches mostly focused on the influencing factors of coal or rock resistivity and the overall characteristics of resistivity during the fracture process of coal or rock. The comparative analysis of resistivity and electromagnetic radiation needs to be further studied at different stages of deformation and failure of loaded coal.

2. Experimental Methods

2.1. Experimental Equipments

The experiment was carried out on the acoustic and electrical experimental system of loaded coal, which was independently designed and developed by coal and rock dynamic disaster laboratory of China University of Mining and Technology (Beijing). The experimental system is shown in Fig. 1. It mainly includes the stress loading system, coal and rock electromagnetic radiation monitoring system, acoustic emission acquisition system, strain acquisition system and electrical parameter monitoring system.

The loading range of stress loading system is 50kN $\sim$ 2000kN and the accuracy is $\pm$ 0.005 kN. The portable electromagnetic radiation monitoring system of EME-HF was adopted for the electromagnetic radiation monitoring. The effective monitoring distance is 7-22m and the sampling frequency is 10MHz. The broadband ring antenna of SAS-560 was used for the device, which can receive two parameters: electromagnetic radiation intensity and pulse number. The HIOKI 3532-50LCR detector was used for the electrical parameter detection and the measurement frequency range is 42khz $\sim$ 5MHz.

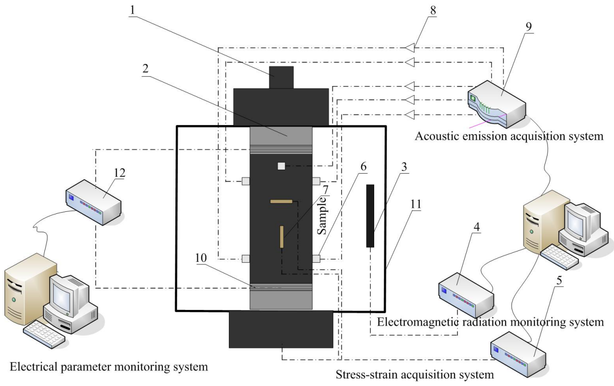


Fig. 1. Structure of acoustic-electrical experimental system for loaded coal or rock

1. Loading system, 2. Load sensor, 3. Electromagnetic coil, 4. Electromagnetic radiation monitoring system, 5. Stress-strain acquisition system, 6. Acoustic emission sensor, 7. Strain sensor, 8. Preamplifier, 9. Acoustic emission acquisition system, 10. Insulating paper, 11. Shielding net, 13. LCR electrical parameter monitoring system.

2.2. Coal Sample Preparation

The experimental coal samples were taken from No.3 coal seam of Yuwu Coal Mine in Shanxi Province and No.4 coal seam of Shadunzi Coal Mine in Xinjiang Province of China. According to the experiment approach of rock (DZ/T 0276.18-2015) with physical-mechanical properties, the coal samples were drilled and cut in the laboratory to make the standard cylindrical coal samples with a size of Φ 50 $\times$ 100 mm.

The accuracy of specimen is required that the ratio of height to diameter is between 2.0 and 2.5, the diameter measurement error along the whole height of sample is $\leq \pm$ 0.3mm, the non-parallelism error of both ends is $\leq \pm$ 0.05mm and the surface roughness error of both ends $\leq \pm$ 0.02mm. The processed coal samples are shown in Fig. 2. According to the industrial analysis method of coal (GB/T 30732-2014), the coal samples were placed in a constant temperature drying oven at 80^o C and dried for more than 24 h for industrial analysis. The moisture, ash, volatile and

Fig. 2. Test samples

fixed carbon contents of coal samples were obtained. These industrial analysis parameters of coal samples are shown in Table 1.

2.3. Principles of Experiment

The electromagnetic radiation and electrical parameters experiment under uniaxial loading was carried out on two kinds of coal samples with natural water content at room temperature. Ten coal samples were divided into two groups from two coal mines. One group of coal samples is bituminous coal from Yuwu Coal Mine in Shanxi Province, and the other group is long flame coal from Shadunzi Coal Mine in Xinjiang. According to the experiment approach of rock (DZ/T 0276.18-2015) with physical-mechanical properties, the stress loading rate was determined as 0.5Mpa/s in the experiment. In order to avoid the influence of end effect, Vaseline was applied to the contact part between the end face of specimen and the compression plate to reduce the friction.

Through a large number of experimental tests during the deformation and fracture of coal under various loading conditions, it was found that a variety of mechanisms led to the electromagnetic radiation phenomenon in the failure process of coal. The resistivity is the main basic parameter to study the propagation of electromagnetic radiation. In this experiment, the variation of resistivity and electromagnetic radiation was monitored at the same time during the failure process of coal and rock.

According to the working principle of LCR testing equipment, the resistivity of coal can be calculated by the following formula [16].

$$R = |Z| \cos\theta \tag{1}$$

$$\rho = |Z| \cos\theta \frac{S}{L} = R\frac{S}{L} \tag{2}$$

Where, R: Resistance value, Ω; Z: Impedance value, Ω; θ: Phase angle, degree; S: Cross-sectional area of sample, m^2; L: Sample length, m; ρ : Resistivity, Ωm.

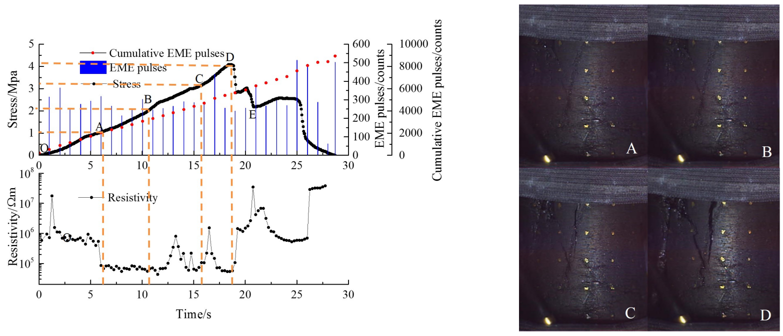
The frequency range of LCR testing equipment is 42kHz-5MHz. Previous studies have shown that the test frequency has a great influence on the electrical parameters of coal and rock. For the loaded coal and rock, the low-frequency electromagnetic radiation signal is mainly studied, so the test frequency is 10kHz in the experiment, which is also the frequency used in the mine direct current exploration [14] . Chen Peng, Meng Lei and other researchers also used this test frequency more often [5, 17–19]. These researches [20, 21] showed that the bedding structure in coal would lead to the obvious directionality of resistivity. The resistivity in parallel bedding direction was less than that in vertical bedding direction. Because the samples used in this experiment were drilled along the vertical bedding direction, the resistivity parameters of coal in vertical bedding direction were studied in the experiment.

3. Results and discussion

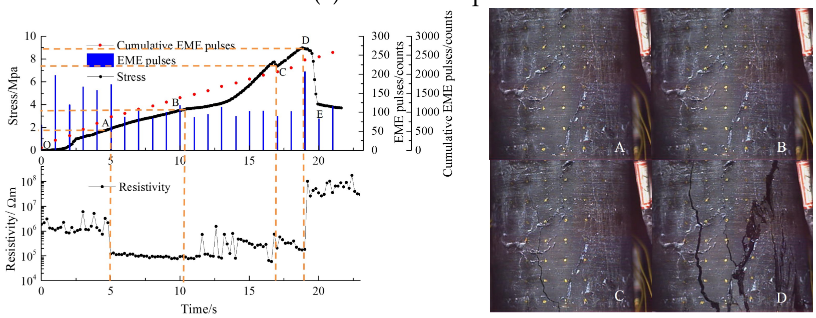
The experimental results of resistivity and electromagnetic radiation were shown in Figs. 3 and 4. During the process of uniaxial compression, the EME pulses of Yuwu and shadunzi samples had two or three peaks respectively. The highest value of y1 was 514 after the stress peak and the highest value of y4 was 207 before the stress peak. The peak values of S1 and S4 were 400 and 702 before the stress peak, respectively. Before the peak stress, the resistivity of two coal mine samples decreased with the increase of stress and increased greatly after the peak stress.

From Figs. 3 and 4, it can be seen that in the initial compaction stage of OA, the EME pulses of both Yuwu and shadunzi samples had several peaks. At this stage, the resistivity of coal fluctuated to a certain extent with the range of 10^5-10^7 ωM. In the elastic stage of AB, the stress-time curve of coal was approximately straight line and the stress rate was close to a stable value. In this stage, the EME pulses number of Yuwu and shadunzi samples decreased, the resistivity decreased significantly, and the variation curve was nearly linear, which was also confirmed and introduced by many researchers [14, 19, 22].

In the yield stage of BC, the stress-time curve of coal deviated from the straight line. The EME pulses of Yuwu and Shadunzi samples changed little compared with the previous stage, the resistivity of Yuwu coal samples fluctuated greatly compared with the previous stage, but the resistivity of Shadunzi coal samples changed little. This may be the main reason for the change of resistivity caused by the formation and steady development of microcracks.

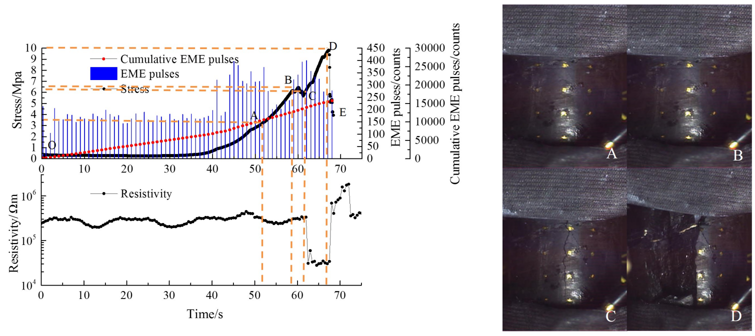


(a) Y1 coal sample

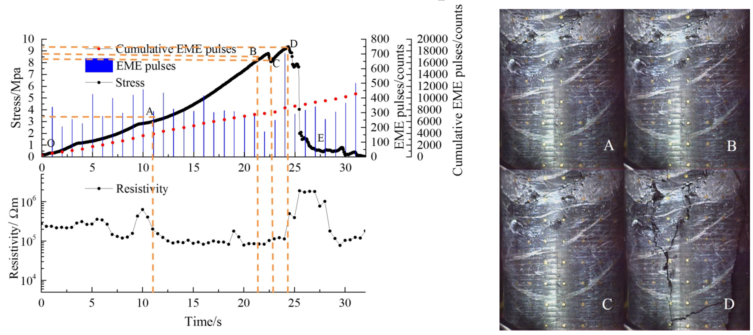


(b) Y4 coal sample

Fig. 3. Resistivity, electromagnetic radiation and crack propagation characteristics of Yuwu samples (A,B,C,D represents the different stress loading points of coal samples and the deformation and fracture diagrams of coal under the corresponding stress loading points)



(a) S1 coal sample



(b) S4 coal sample

Fig. 4. Resistivity, electromagnetic radiation and crack propagation characteristics of Shadunzi samples (A,B,C,D represents the different stress loading points of coal samples and the deformation and fracture diagrams of coal under the corresponding stress loading points)

Table 1. Proximate analysis of coal samples

Serial number	Coal Mine	Types	$M_{ad}/\%$	$A_{ad}/\%$	$V_{ad}/\%$	$V_{daf}/\%$	FC/%
1	Yuwu	Lean Coal	0.35	11.36	21.56	24.42	66.73
2	Shadunzi	Long Flame Coal	2.03	2.86	31.53	33.15	63.58

In the unstable development stage of CD, the EME pulses of Yuwu and Shadunzi samples was in the range of 400 to 700 before the peak value of stress, and there was a peak. From the peak value to the stress peak value, the pulse number also appeared a quiet period, the resistivity decreased in this stage, and the formation speed of internal cracks in coal was accelerated. The cracks showed the unstable development. In the destruction stage of DE, after the peak value of D point, the internal microcracks would form the main cracks with the increase of external stress. In this stage, the number of EME pulses of Yuwu and Shadunzi samples decreased significantly and the resistivity increased significantly.

4. Conclusions

Through the analysis of resistivity and electromagnetic radiation during the process of uniaxial compression of coal, the conclusions are as follows.

1. The general trend of resistivity and electromagnetic radiation of two different coals has similar variation regularity, but their characteristics are different in different stages.

2. In the initial compaction stage, the EME pulses of two kinds of coal increases and reaches several peaks. The resistivity fluctuates in a certain range. In the elastic stage, the EME pulses and change of resistivity decrease greatly and the change curve is close to be linear. In the yield stage, the EME pulses changes little compared with the previous stage, and the resistivity fluctuates to a certain extent compared with the previous stage. In the unstable development stage, the EME pulses has a peak before the stress reaches the peak, there is a quiet period of pulses before the stress peak, and the resistivity has a downward trend before the stress peak. After the stress peak, the convergence and penetration of macro-fractures lead to the significant decrease of pulse number and the significant increase of resistivity.

3. Through the comparative study of resistivity and electromagnetic radiation pulse in each stage during the deformation and fracture of coal under compression, it is found that the increasing area of electromagnetic radiation pulse generally appears in the area with large changes of resistivity.

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