Experimental Research on Precursory Characteristics of Macroscopic Deformation of Coal and Rock Failure

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Abstract. The research on precursory characteristics of coal and rock failure is of great significance for monitoring and early warning of disaster of surrounding rock. In this paper, the macroscopic deformation process of coal and rock under uniaxial compression is tested, and the evolution rule of the quantity, velocity and acceleration of their deformation is studied. The relationship between specimen surface damage and macroscopic deformation is investigated by image processing and analysis method. The research indicates that the macroscopic deformation indexes of coal and rock failure zones have significant changes before cracking, showing regular dynamic deformation characteristics, which could be precursory information of coal and rock failure.

Keywords: roadway deformation; coal and rock; deformation and failure; visualization; damage

1. Introduction

With the increase of depth and intensity of coal resources mining, mining conditions become more and more complex (Xie, et al. 2015 & He, et al. 2013), meanwhile, mine pressure increases, roadway deforms severely, and surrounding rock disasters occur frequently (Chen, et al. 2013, Li et al. 2005 & Yang et al. 2015). The instability and failure of surrounding rock, especially the sudden and unpredictable surrounding rock, could block underground traffic, increase mine ventilation resistance, production equipment, cause casualties and induce secondary disasters, which seriously threaten the safety of coal mine production. Therefore, it is necessary to study the precursory information of surrounding rock instability to realize the early warning of disasters.

The deformation and failure of coal and rock material is a process from gradual change to abrupt change, as well as a process from uniform deformation (or approximately uniform deformation) to instability by localization of the deformation (Liu, et al. 2010 & Qian, et al. 2016). The existing research on localization deformation seems mostly focus on the strain field of sample surface at the mesoscopic and microcosmic scales, which is not related to macroscopic deformation of coal and rock (Xia, et al. 2016, Li, et al. 2016, & He, et al. 2015). Internally, volume elements of coal and rock material become deformed under uniaxial compression, and the crack between volume elements propagates. The aggregation of volume elements deformation and crack propagation constitutes the macroscopic deformation of coal and rock materials, which characterizes the damage degree of interior
materials. Therefore, by exploring the relationship between the deformation localization region and macroscopic deformation, the relationship between the internal damage and macroscopic deformation could be established, for the early warning of the failure of coal and rock.

Based on the foregoing analysis, in this paper, the macroscopic failure process of coal and rock under uniaxial compression has been tested, researching the evolution rule of the quantity, velocity and acceleration of their deformation, and the critical value of deformation index in each stage of deformation and failure is determined. The relationship between surface damage and macroscopic has been studied by image processing analysis method. Finally, the macroscopic deformation precursor characteristics of coal and rock failure are determined.

2. Experiment and Methods

2.1. Sample Preparation
There are two kinds of samples used in the experiment: raw coal sample and sandstone sample. The coal sample is taken from Sanhejian Mine in Xuzhou, and the rock sample is taken from 85th roof strata in Taoshan mining area of Longmei Group. The samples were processed and prepared in the State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology. The massive coal and rock samples obtained from underground were respectively processed into standard simples of 50mm×50mm×100mm and Ø50mm×100mm, with the flatness error of both ends less than 0.02 mm.

2.2. Experimental System
The experimental system mainly includes the experimental system of coal and rock deformation and failure and the visual monitoring instrument. The coal and rock deformation and failure experimental system mainly consists of loading system and coal and rock deformation measurement system. The loading system adopts WAW-600 microcomputer-controlled electro-hydraulic servo universal testing machine. The deformation measuring system consists of Epsilon 3542RA and Epsilon 3544 extensometers. The extensometer is connected with the full digital extensometer of the testing machine to realize the dynamic measurement of the axial and radial deformation of coal and rock samples.

The visual testing instrument for deformation and failure of coal and rock adopts fixed focal lens without distortion and high-speed CCD camera, monitoring the deformation and failure process of coal and rock in real time, realizing the simultaneous observation of macroscopic deformation and surface damage. The quantitative relationship between surface crack propagation and macroscopic deformation was studied by image processing and analysis technology, analysing the response correlation between surface damage and macromechanics.

2.3. Experimental Scheme
(1) Experiment deformation and failure of coal and rock
Uniaxial compression tests were carried out on coal and rock samples. Simultaneously, the axial and radial strains of the samples were measured by extensometer (see Figure 1).

(2) Visual experimental scheme for deformation and failure of coal and rock
1) Surface damage observation of materials
Fissure extraction algorithm flow: ① the frame image is converted into binary image, and then inverse calculation; ② the contour of binary image is obtained; ③ the morphological method is used to extract the fissures, calculate the length and width of the fissures, and calculate the degree of surface damage.

2) Macrometric measurement of material deformation
The edge of the samples was obtained by the edge detection algorithm for image processing. Then the sample is divided into five zones, each with a line of measurement (the line of measuring points on the edge of the sample). By using the geometric relationship among camera, sample, measuring point and line, the change of the length of the measuring line is transformed to the change of the diameter of
each area of the samples. Finally, the regional measurement of macro-deformation of the simples was realized.

![Figure 1](image.png)

**Figure 1.** Deformation and failure experiments of coal and rock (the rock sample is on the left and coal samples on the right).

### 3. Macro-Deformation Law of Coal and Rock before Failure

#### 3.1. Coal Sample

The load-time curve, axial strain curve, axial strain velocity and acceleration curve, radial velocity and acceleration curve, during the process of loading and destroying coal samples, are given in Figure 2.

It can be seen from Figure 2 (a) that the peak load occurs in 529s and the load value is 43.06kN ($F_{\text{max}}$). As is shown in Figure 2 (b), axial strain occurs before point A, which corresponds to the closure of internal defects and voids in coal and rock mass at the initial stage of loading. The relationship between the axial strain and the radial strain in AB stage is linear, simultaneously, the deformation is in the elastic stage. Point A is the starting point of the elastic deformation. The load at point A is 0.69$F_{\text{max}}$, the axial strain at point A is 19.36% of the axial strain at 529s, and the corresponding radial strain is 1.42% of the radial strain at 529s. The radial strain of BC stage increases significantly, and the curve of axial strain and radial strain deviates rapidly from the straight line of AB section. In this stage, the specimen is in the transition stage from elastic to plastic deformation, and the micro cracks in the specimen begin to germinate and propagate steadily. Point B is the starting point of crack development in the specimen. The load at B-point is 0.94 $F_{\text{max}}$, the axial strain is $0.5\varepsilon_{\text{hmax}}$, and the radial strain is 0.07 $\varepsilon_{\text{rmax}}$. The radial strain of CD stage increases sharply further, while the axial strain increases slowly, and reaches the maximum $F_{\text{max}}$ at point D. Point C is the yield point of deformation and failure of specimens. At Point C, the specimens are loaded at 0.99 $F_{\text{max}}$, the axial strain at Point C is 0.84$\varepsilon_{\text{hmax}}$, and the radial strain is 0.71$\varepsilon_{\text{rmax}}$. 

![Loading-time](loading-time.png)

(a) loading-time

![Axial-radial strain](axial-radial-strain.png)

(b) axial-radial strain
3.2. Rock Sample
The load time curve, the axial strain curve, the axial strain velocity and acceleration curve, and the radial strain rate and acceleration are shown in Figure 3.

Figure 3 (a) and (b) demonstrate that the load-time curves and radial-axial strain curves of rock samples during loading are similar to those of coal samples. The strain velocity and acceleration are stable in the early stage of loading, and fluctuate with the increase of load. In this process, A, B and C are demarcation points of different loading stages, as well as demarcation points of strain velocity and acceleration changes.

Analyzing the process of deformation and fracture of coal and rock, it can be seen that the process of loading and failure of coal and rock shows distinct stage characteristics. In this process, the axial and radial strains and their strain velocities and accelerations show different characteristics in different stages, which can be used as the basis for stage division. Axial and radial strains reflect the degree of material deformation and failure, and can be used as macro parameters of material failure. The variation of strain velocity and acceleration reflects the dynamic characteristics of coal and rock failure under load, and can be used as the precursor information of coal and rock failure.
4. Visual Analysis of Deformation and Fracture of Coal and Rock
The macroscopic observation of the deformation of coal and rock samples under loading is illustrated in Figure 4.

It can be seen that the deformation of each region of the specimen is not uniform. Some regions have earlier deformation, from where it can be seen more cracks and more serious damage. It is possible for any crack to develop into a main crack leading to the overall failure of the specimen, therefore, the average diameter deformation curve can hardly reflect this process.

According to all the frame images in the process of specimen deformation and failure, the diameters of five regions are calculated according to the coordinates of measuring points each time. The av-
average diameters are calculated and the average diameters are obtained as shown in Figure 5. The diameter deformation curves of each region are obtained as shown in Figure 6.

Figure 6 shows that the region 1 is deformed first, then the region 2 is deformed because they are the first to bear an active load. The deformation of the region 3 and region 4 is larger than that of the region 1, because the region 1 is constrained by the horizontal friction resistance of the pressure plate of the testing machine, and the deformation is limited to a certain extent.

![Figure 4. Deformation and Failure Process of Sample](image)

(a) 1147th frame image  
(b) 2001th frame image

(a) average diameter

![Average diameter vs Time](image)
Figure 5. Average diameter deformation curves.

Figure 6. Diameter deformation curves.
(a) deformation velocity/acceleration-time of region 1

(b) deformation velocity/acceleration-time of region 2

(c) deformation velocity/acceleration-time of region 3
Figure 7 indicates that the initial deformation and failure of the simple occur in the region 1. The diameter of the region 1 is larger than that of the other regions. The first peak of the deformation velocity and acceleration curve of the region 1 is earlier than that of the other regions. It can be seen from the real-time image that the cracks first appear in the region 1. Deformation and failure are transmitted downward from the region 1, which is shown in the figure that the diameter of each region decreases from the region 1 before 157 seconds, and the peak velocity and acceleration of other regions except the region 5 lag behind. After the development of the main fissures, the deformation of the third and fourth regions is the strongest. In the graph, the diameter of the main fissures is larger than that of other regions, and peak velocity and acceleration are larger than those of other regions.

There is a close relationship between the quantity, velocity and acceleration of deformation and simple failure. Comparing the measured curve with the real-time image, the radial deformation of the corresponding area increases obviously, the deformation velocity fluctuates greatly, and the number of times that the deformation acceleration exceeds the average amplitude of the stable stage increases apparently, especially when the main crack develops to the whole failure of the specimen.
5. Conclusions
(1) The failure process of coal and rock under loading shows apparently stages characteristics, and the axial and radial strains and their strain velocities and acceleration show different characteristics in different stages. The axial strain response is obvious in the compaction stage and the elastic deformation stage. The axial deformation is larger than the radial deformation, and the radial deformation is larger than the axial deformation in the plastic deformation stage, especially the radial deformation before yielding is more sensitive. During the loading process of coal and rock samples, when the deformation accumulates to a certain extent, the deformation velocity begins to fluctuate sharply, and then rises. The number of times that the deformation acceleration exceeds the average amplitude during the stable period increases greatly.

(2) The relationship between surface damage and macro-deformation is studied by image analysis method. It is found that the macro-deformation index of the failure area changes significantly before the local failure of coal and rock specimens. There is a close relationship between the quantity, velocity and acceleration of deformation and simple failure. Comparing the measured curve with the real-time image, the radial deformation of the corresponding area increases obviously, the deformation velocity fluctuates greatly, and the number of times that the deformation acceleration exceeds the average amplitude of the stable stage increases obviously, especially when the main crack develops to the whole failure of the specimen.

(3) In the process of coal and rock failure under load, the axial and radial strains and their strain velocities and accelerations show different characteristics in different stages, which can be used as the basis for stage division; the axial and radial strains reflect the degree of material deformation and failure as macro-parameters of material failure. The variation of strain velocity and acceleration reflects the dynamic characteristics of coal and rock failure under load, and can serve as the precursor information of coal and rock failure.

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