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ORIGINAL PAPER

EXPERIMENTAL INVESTIGATION INTO DYNAMIC DAMAGE MECHANISM OF ROCK-COAL-ROCK COMBINATIONS BASED ON DIGITAL IMAGE CORRELATION METHOD

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ABSTRACT

In recent years, the dynamic damage of coal rock mass induced by deep mining disturbance has become increasingly serious. To study the mechanical properties of coal-rock combination under SHPB impacts, digital image correlation technology was used to investigate the dynamic evolution laws of strain field, displacement field, crack initiation and propagation of rock-coal-rock combination at different loading rates. Through qualitative and quantitative analyses, the following research results are obtained. It is concluded that different crack evolution and propagation of the composite are presented due to the increase of load, which have three stages: uniform deformation, local deformation and overall crushing. With the increase of strain rate, the shorter the time to reach the uniform strain, the faster the crack evolution and propagation, and the more obvious the degree of fracture of the specimen. Under the impact load, the specimens of rock-coal-rock assemblage show axial splitting failure, and the cracks in the middle coal body appear first and the damage is the most serious, and the coal body also shows ejection phenomenon under high-speed impact. The experimental results can improve the occurrence mechanism of dynamic phenomena such as rockburst and coal and gas outburst, and provide data accumulation and reference for coal mine safety production and mine disaster prevention and mitigation.

1. INTRODUCTION

In the long process of geological movement, the naturally formed coal and rock masses are often naturally distributed with anisotropic micro cracks and holes, etc. When subjected to external impact loads, these micro defects will inevitably form cracks or joints with larger scales and richer forms. When the damage reaches a certain extent. The destruction of the integrity and mechanical properties of coal rock mass around the mining space will threaten the safe mining of underground coal resources (Ranjith et al., 2017; Mazaira and Konicek, 2015; Bieniawski, 1968). Due to the limitation of sampling rate, analysis accuracy and scale, it is difficult for traditional research methods to achieve high-precision holographic capture of fracture evolution. Digital image correlation (DIC) technique, as a practical and effective quantitative measurement tool for surface deformation of planar objects, has been widely recognized and applied in the field of experimental mechanics (Chen et al., 2017; Okubo et al., 2019). Based on DIC technology with the existing macroscopic fracture failure mechanism, the microscopic progressive damage law of coal and rock mass will become a hot research topic in the field of coal and rock mass damage research, which is significant to guide practical engineering problems. To study the damage evolution mechanism of single coal sample or rock sample, experts and scholars have conducted a large number of studies based on triaxial, biaxial and uniaxial experiments, which show rich research results (Pan et al., 2016; Blaber et al., 2015; Gao et al., 2015; Wang et al., 2018). However, few studies have been conducted on the dynamic damage and fracture mechanism of rock sample, coal sample and rock sample combination. The observation methods and techniques of crack propagation and damage process in laboratory experiments have become an important topic in the current research direction of coal rock fracture. Xu et al. (2018) used DIC method to study the crack growth and damage evolution of rock-like materials under uniaxial compression, and obtained the full-field displacement and strain during rock-like failure. Mi et al. (2021) used the digital image correlation method to analyze the dynamic evolution laws of crack onset and expansion of different types of rocks under the load of three-point bending and uniaxial compression, providing data reference for disaster prevention and reduction and engineering construction. Wang et al. (2018) used the digital image correlation method to conduct an experimental study on the strain localization process of coal samples under uniaxial compression, and obtained the correlation between the

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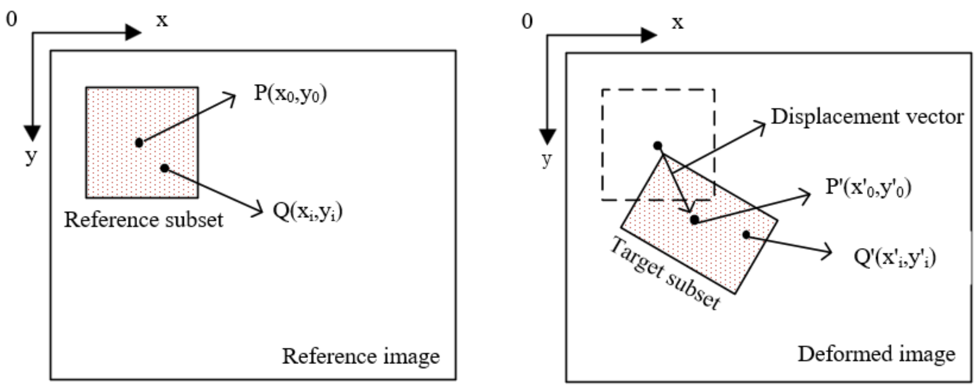

Fig. 1 Diagram of reference subarea and target subarea center point change.

coefficient of variation of the maximum shear strain and the longitudinal stress. Chen et al. (2019), Zhang et al. (2017), Wang et al. (2018), Li et al. (2021) and many other scholars have made a lot of research achievements in fracture evolution and damage deformation of rock and single coal by using digital image correlation method.

In order to study the dynamic damage mechanism of rock-coal-rock assemblages under impact loads, dynamic impact loading tests of rock-coal-rock assemblages under different impact loading rates were carried out in this paper. DIC method was used to track the crack expansion of coal-rock assemblages in real time during the experiment. The crack growth and damage of specimens under different loading rates are analyzed from the perspective of micromechanics, because the crack growth evolution of coal rock mass is closely related to coal mine accidents. Therefore, through this study to improve the understanding of coal rock failure mechanism, to provide data accumulation and reference for mine disaster prevention.

2. BASIC PRINCIPLE OF DIGITAL IMAGE CORRELATION (DIC) METHOD

Digital image correlation (DIC) method is a non-contact optical measurement method often used in experimental mechanics and related engineering research fields for material deformation measurement. It was first proposed by Yoneyama et al. (2006) in Japan and Peters et al. (1983) in the United States in the 1980s. With the development of science and technology such as digital image and the optimization of relevant calculation method theory, DIC method has achieved significant improvement in calculation efficiency and measurement accuracy. Compared with other measurement methods, DIC method has the advantages of high accuracy, high automation, less interference factors, real-time full-field measurement, etc. Extensive and in-depth research has been carried out in the fields of geotechnical engineering, composite materials, biomedicine and metal materials (Peters and Ranson, 1982; Pan et al., 2009).

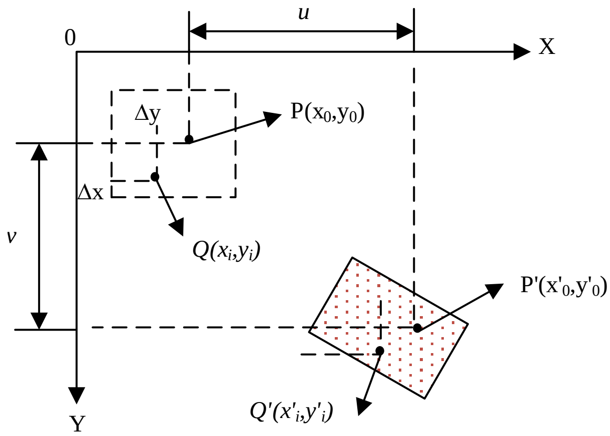

Fig. 2 Position relation of each point in the region before and after specimen deformation.

The principle of DIC method is to make artificial speckle images with certain feature points or natural speckle images on the surface of the object to be tested according to the requirements. By using the changes of the two images before and after the deformation of the part to be tested, the spatial position of the spots before and after the deformation can be tracked and calculated through image matching method and registration calculation theory. The strain field and displacement field of the specimen surface are obtained.

The speckle image distribution before and after deformation of the specimen is called the reference image and the target image, as shown in Figure 1. In the reference image, a reference subarea of n*n pixels is taken. In the reference subarea image, there is a reference subarea center point $P(x_0, y_0)$ and the any point around the P point $Q(x_i, y_i)$, the corresponding coordinates of points P and Q in the target image subregion after object deformation are $P'(x'_0, y'_0)$ and $Q'(x'_i, y'_i)$. Through the continuity hypothesis theory, the series of points around the center point of the reference subregion before deformation or the adjacent points around the center point after deformation are calculated.

The position changes of each pixel before and after specimen deformation are shown in Figure 2.

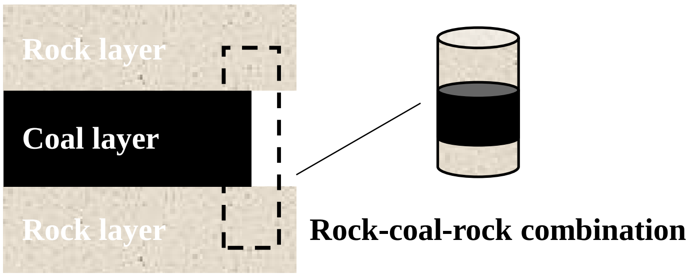

Fig. 3 Structural model of rock-coal-rock combination.

Fig. 4 Rock-coal-rock ‘sandwich’ structure.

The coordinates of the P' and Q' points in the target subregion are satisfied:

$$\begin{cases} x'_0 = x_0 + u \\ y'_0 = y_0 + v \end{cases} \tag{1}$$

$$\begin{cases} x'_i = x_i + u_Q \\ y'_i = y_i + v_Q \end{cases} \tag{2}$$

u、v——The displacement of the P' points on the x and y axes;

u_Q、v_Q——The displacement of the Q' points on the x and y axes;

The gray level of Q points in the area before and after image deformation can be calculated as:

$$f(Q) = f(x_i, y_i)$$
$$g(Q') = g(x'_i, y'_i) \tag{3}$$

f、g——Gray distribution of image before and after deformation;

If $u_Q = u + u_x \Delta x + u_y \Delta y$

$v_Q = v + v_x \Delta x + v_y \Delta y$

$$\Delta x = x_i - x_0, \quad \Delta y = y_i - y_0, \tag{4}$$

Define $\bar{P} = [u, u_x, u_y, v, v_x, v_y]^T$ as the position vector of the displacement variable,

To accurately calculate the displacement vector of the specimen, it is necessary to find the one-to-one correspondence between the points in the reference subregion and the target subregion in the image. The values are calculated using the iterative algorithm, and then the image correlation is calculated using the minimum value of the correlation coefficient.

$$C(f, g) = C(x_i, y_i, x'_i, y'_i) = C(\bar{P}) \tag{5}$$

$$\frac{\partial C}{\partial \bar{P}} = 0 \tag{6}$$

The calculation of strain field of the specimen is based on the calculation of displacement field. The strain field is measured by the displacement measurement and the numerical differential calculation (Pan et al., 2005).

3. BASIC PRINCIPLE OF DIGITAL IMAGE CORRELATION METHOD

3.1. *SPECIMEN PREPARATION*

The coal and rock samples used in the test specimen were taken from 13-1 coal seam of Zhangji Coal Mine, Huainan. The coal and rock samples in the test specimen were drilled from the top and bottom rock samples of the same coal seam, and the samples were cut into thin slices of equal height and carefully polished. To achieve the accuracy of the experiment, the overall thickness of the rock-coal-rock assemblage was 30 mm, and the thickness of each piece of coal and rock was controlled to 10 mm. The assemblage was bonded with epoxy resin binder to ensure the integrity of the assemblage specimen and its close to the actual state. Meanwhile, the parallelism error of the two sections of the specimen was required to be less than the standard value of 0.02 mm. The error of the two ends perpendicular to the axis of the rock-coal-rock composite specimen is not more than 0.25°, which meets the standard requirements of rock mechanics test, as shown in Figures 3 and 4.

Fig. 5 Speckle making process.

To ensure the accuracy of the digital image correlation method, it is crucial to control the speckle size and density on the specimen surface, because the quality of speckle production on the specimen surface directly affects the experimental measurement results. To avoid the glossy paint will reflect light and appear mirror effect, this experiment chooses matte paint as the plate making speckle material. Since the natural markings or surface colors of rock and coal are dark, in order to improve the experimental accuracy, a layer of white matte paint is first sprayed on the surface of rock-coal-rock assembly specimens, and after drying, random spots are sprayed on the surface of specimens with black matte paint. At the same time, a spot is controlled to account for about 3 pixels, and the speckle distribution is uniform and the density is moderate. This process is repeated for 3-4 times. Finally, the spot control process is completed, as shown in Figure 5.

3.2. CONSTRUCTION OF EXPERIMENTAL SYSTEM

The experimental measurement system is composed of dynamic loading system, data acquisition and analysis system, high-precision and high-speed camera observation system and experimental safety protection system, as shown in Figures 6 and 7. The Φ75mm Split Hopkinson Pressure Bar (SHPB) from the laboratory of School of Safety Engineering of Anhui University of Science and Technology is used as the impact loading system equipment. The resistance strain gauge and semiconductor strain gauge are bx120-2 and HU101B-120 respectively, and the experimental data are collected and analyzed by DHHP-20 hyperdynamic data acquisition system. The camera equipment selected for this experiment is the world's top high-speed camera of FASTCAM SA-Z series developed by PHOTRRON Company in Japan, equipped with CMOS sensor, the maximum resolution is 1024*1024 pixels, the full frame value is 20000 FPS, the shortest exposure time is 159 nsec, and the shooting speed can be up to 224,000 fps. The data and images were analyzed with two fill lights and the software of the 3D Digital Image Correlation Computing System (DIC-3D system) to record and analyze the cracking development process and the final damage state of the specimen. Due to the brittle material of coal and rock, the anti-impact shelter facilities, fragment collection system and protection sleeve were independently designed to protect the safety of experimental personnel, equipment and debris collection.

Fig. 6 Test set system.

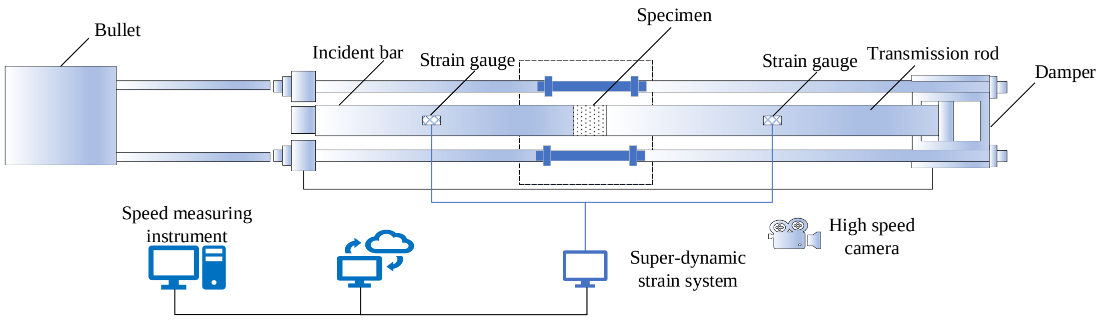

Fig. 7 Diagram of dynamic loading experimental device system.

3.3. EXPERIMENTAL PROCESS

The DIC experiment process is mainly divided into the following four steps:

1. Experiment preparation. Preparing specimens, bonding and polishing the rock-coal-rock assemblage according to the size and standard required by the experiment, and producing speckle images with moderate density and uniform size, and then clamping the completed assemblage specimen to the dynamic loading experimental equipment.
2. Debugging equipment. According to the experimental arrangement, the installation and debugging of high-speed camera, light filling equipment, velocity measurement system, data acquisition and analysis system, sensor and other equipment was completed, and the astigmatism state of the light filling lamp was adjusted to the maximum value, and the aperture was adjusted to make the image display of the specimen surface reach the clearest state, and the image acquisition software was set relevant parameters to obtain reference images.
3. Experiment starts. After the SHPB experiment system is started, the high-speed camera will automatically trigger the work and collect images, and automatically save them to the storage device.
4. Data analysis. Displacement and strain analysis, using DIC analysis software to read images, select reference images, AOI selection, selection of related parameter functions, operational analysis and other processes. The high-speed camera control interface and DIC data analysis interface are shown in Figures 8 and 9.

4. EXPERIMENTAL RESULTS

The dynamic loading experiment of rock-coal-rock composite changes the impact velocity of the bullet by changing the cylinder pressure of the Hopkinson pressure bar test system, so as to obtain the dynamic mechanical properties of rock-coal-rock composite under different strain rates. In the experiment, the assembly was loaded at four speeds respectively, and the image was collected by the experimental system in the whole process, and the crack expansion and change of the assembly can be clearly observed.

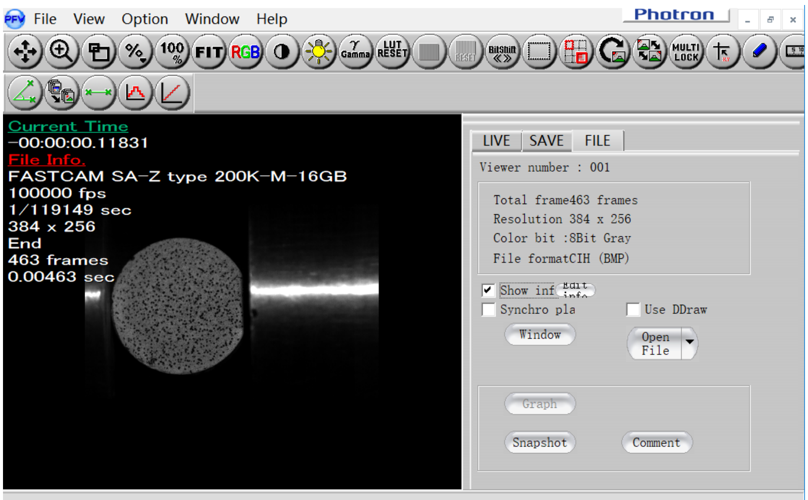

Fig. 8 High-speed camera control interface.

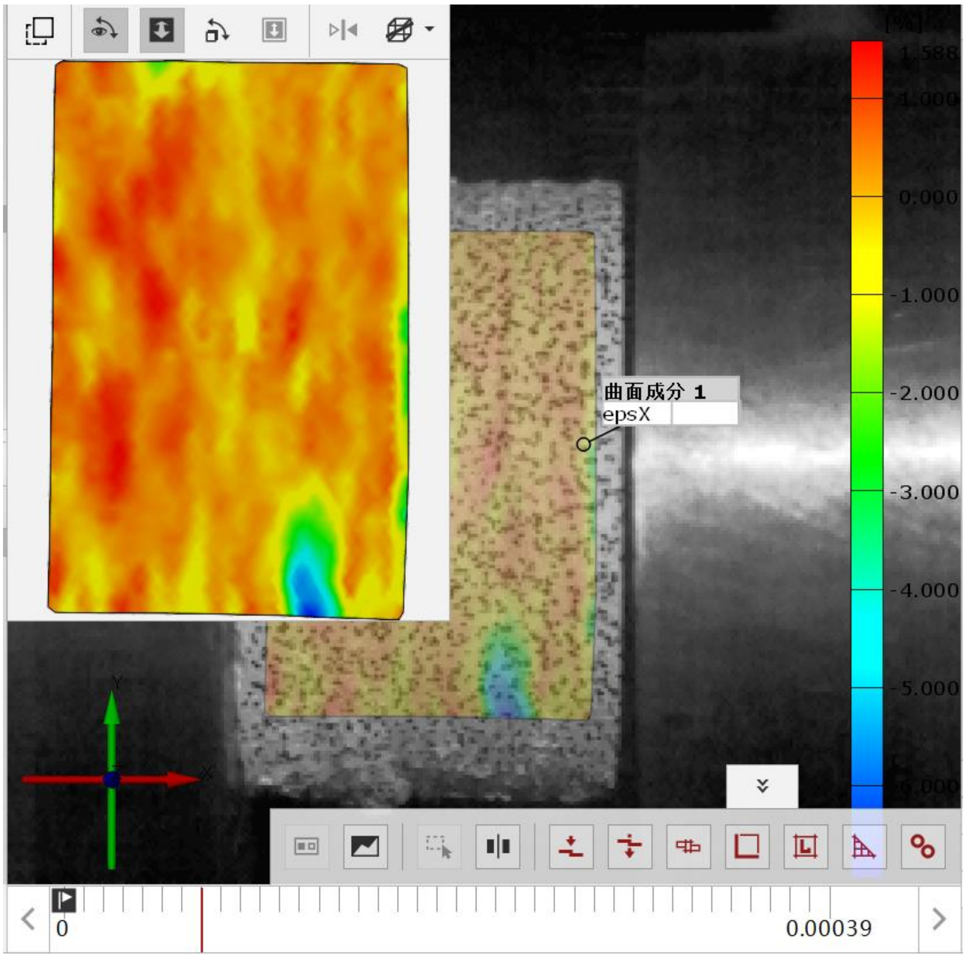

Fig. 9 DIC data analysis interface.

Table 1 Specimen test parameter.

Number	Height /mm	Diameter /mm	Quality /g	Ratio of Length and diameter	Driving pressure /MPa	Bullet velocity /ms^{-1}	Mean strain rate
YMY-1	30.06	49.97	130.4	0.60	0.1	5.41	58.7
YMY-3	30.08	49.93	128.7	0.60	0.2	8.58	237.4
YMY-4	30.05	49.95	130.2	0.60	0.3	10.85	354.3
YMY-5	30.17	49.98	133.9	0.61	0.4	13.57	471.2

4.1. *FAILURE ANALYSIS OF ROCK-COAL-ROCK ASSEMBLAGES UNDER DIFFERENT LOADING RATES.*

Figure 11 to Figure 14 respectively show the failure states of rock-coal-rock assemblages under different loading rates. According to the experimental data analysis, most of the rock-coal-rock assemblages under the impact load show axial splitting states, because the impact loading experiment is carried out along the axial direction, and the side surfaces of the assemblages are all free surfaces. In addition, the stress wave under impact compression appears as tensile stress wave after reflection, and the rock-coal-rock assemblage is prone to tensile failure. Because the strength and hardness of rock are much larger than that of coal, in the process of impact loading of assembly, several groups of experiments show that the middle coal body cracks first and the rupture state is the most obvious. A phenomenon of debris ejection is also presented under high-speed loading.

Figures 10 and 11 show that the coal body in the middle of the rock-coal-rock assemblage breaks first and a large number of fragments are thrown around. The rocks at both ends are in a state of splitting, and the failure time of the rock body at both ends is longer than that of the coal body in the middle. This experimental phenomenon can be used to explain the dynamic phenomenon of coal and gas outburst or rock burst under dynamic load or impact load.

As can be seen from Figures 13 and 14, when the assembly is in the state of high-speed impact, it is not obvious that the crack of the assembly starts from the coal body to the rock mass at both ends. Under this parameter state, the fracture form of the coal-rock-coal

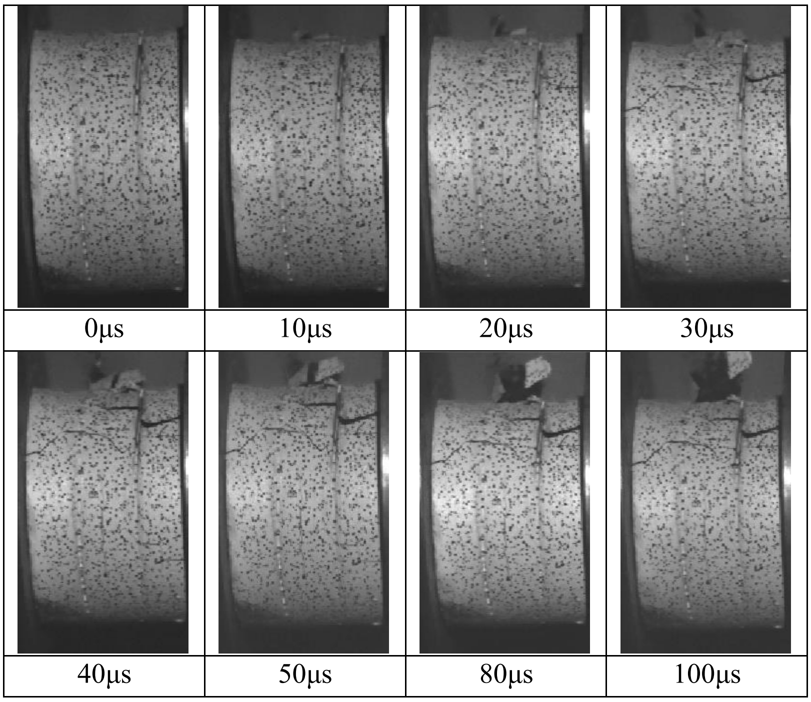

Fig. 10 The crack propagation occurs when the impact velocity is 5.411 m/s.

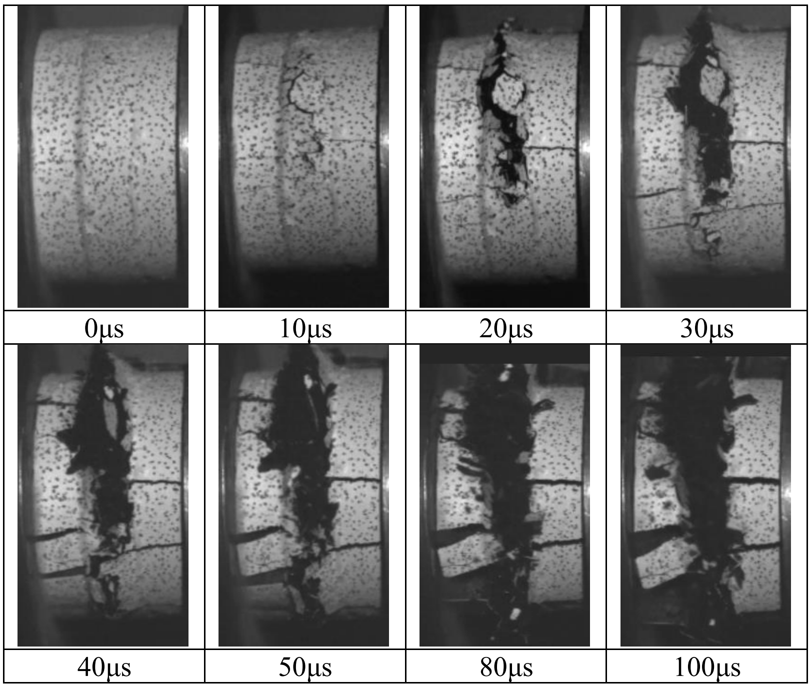

Fig. 11 The crack propagation occurs when the impact velocity is 8.584 m/s.

assembly is closer to a simple rock mass fracture phenomenon. Through the above sets of experiments, it can be clearly found that the greater the impact load, the greater the crack growth rate of rock-coal-rock composite, the faster the instability of the composite, and the more obvious the degree of breakage. When the impact velocity is 5.411 m/s, the significant failure of the combined specimen is about 80 us. When the impact velocity increases to 13.57 m/s, the significant failure time of the combined specimen is shortened to about 40 us. Meanwhile, it shows that with the increase of impact load, the fracture state of rock-coal-rock composite tends to be more the same as that of a single rock mass. The test results verify that the high impact dynamic load has transient destructive effect on the coal and rock samples.

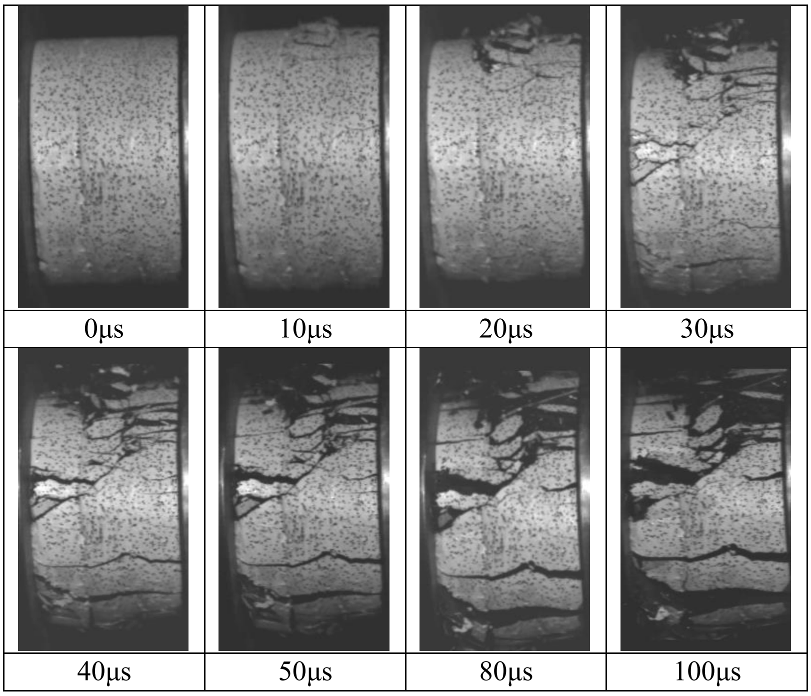

Fig. 12 The crack propagation occurs when the impact velocity is 10.85 m/s.

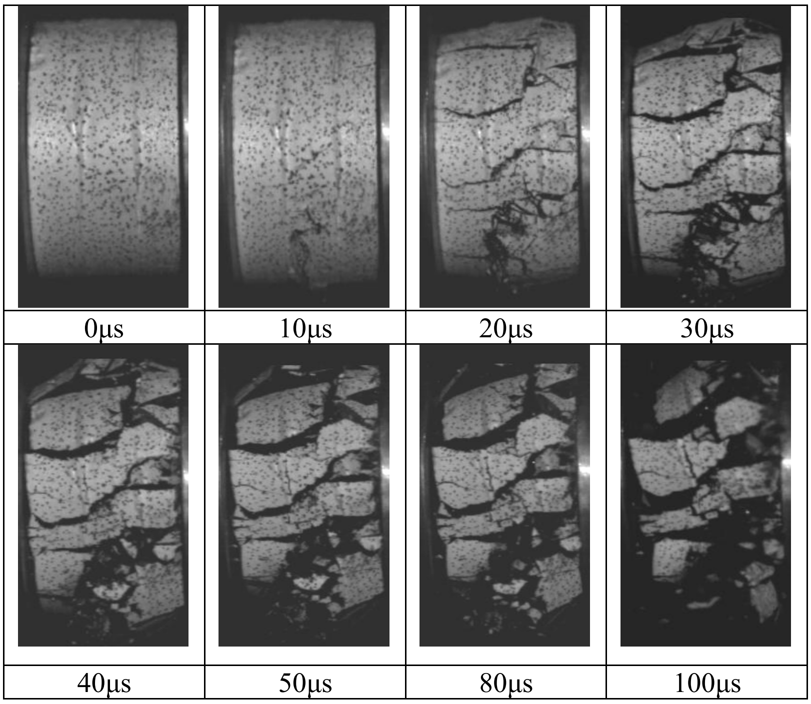

Fig. 13 The crack propagation occurs when the impact velocity is 13.57 m/s.

4.2. DIC ANALYSIS OF FAILURE OF ROCK-COAL-ROCK ASSEMBLAGES UNDER DYNAMIC LOAD

4.2.1. DISPLACEMENT FIELD ANALYSIS OF FAILURE PROCESS OF ROCK-COAL-ROCK ASSEMBLAGES

Figures 14 and 15 show the horizontal displacement field of rock-coal-rock assemblages under impact loads. It can be clearly seen from the two figures that when the loading action time is 15 μs, the maximum displacement of the assembly specimen is 0.107 mm when the bullet impact velocity is 8.584 m/s; when the bullet impact velocity is 13.57 m/s, the maximum displacement of the assembly specimen can reach 0.312 mm. The displacement of other groups of specimens increases with the increase of impact velocity at the same time. It can be seen from Figures 14 and 15 that under two different impact velocities, the assembly specimen presents a large displacement area in the lower left

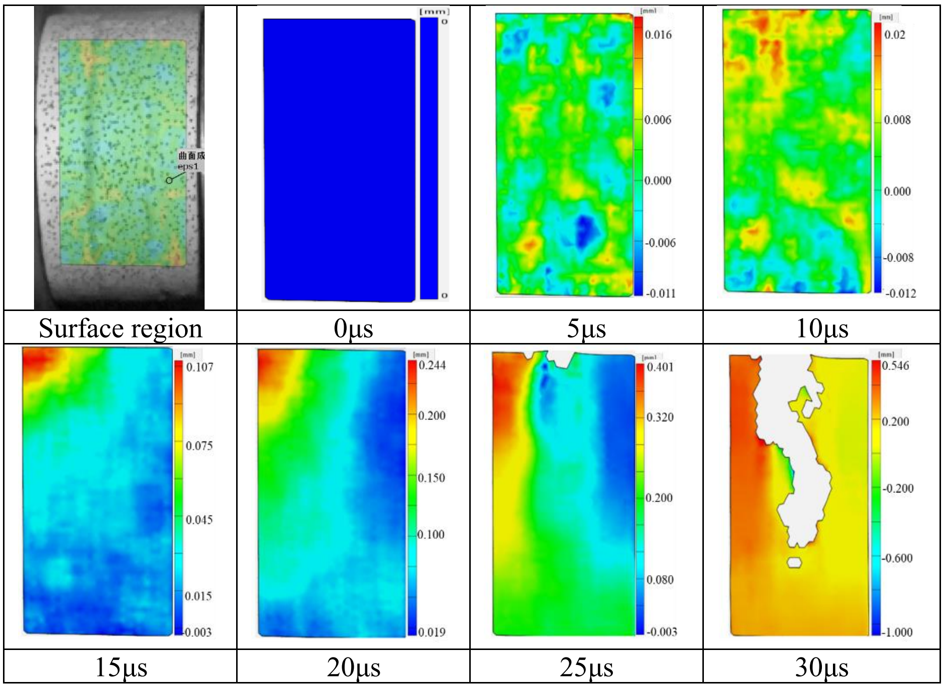

Fig. 14 Displacement field analysis in X direction of rock-coal-rock composite with impact velocity of 8.584 m/s.

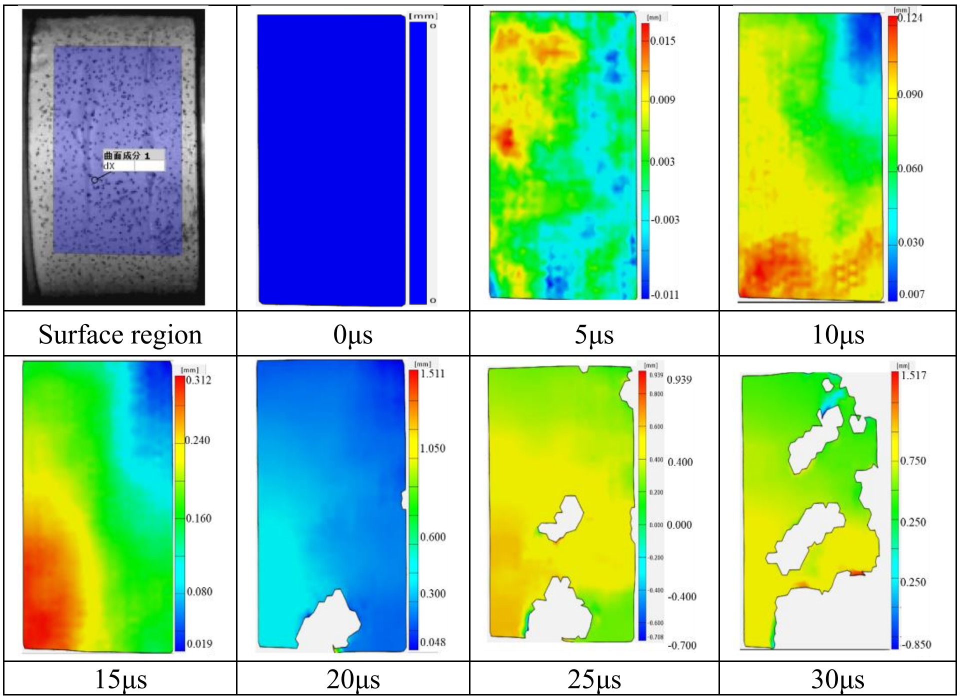

Fig. 15 X-direction displacement field analysis of rock-coal-rock assemblage with impact velocity of 13.57 m/s.

corner and upper left corner respectively, mainly because the impact load is applied from the left end face of the assembly specimen, and the hardness of the rock is higher and more brittle than that of the coal, resulting in local burst phenomenon. The phenomenon caused by the redistribution of stress in the rock-coal-rock assemblage; The reason for the burst may be the existence of pores or cracks in the rock mass, or the uneven distribution of minerals in the assembly specimen, which leads to the local stress concentration of the specimen. At the same time, there are non-standard placement of assembly specimens in the experiment, which leads to the uneven application of axial load on the section of assembly. Figures 14 and 15 show that after the heterogeneous deformation of the assembly specimen in the first stage, the internal deformation of the assembly specimen in the later stage is propagated and reflected several times by stress waves, and the internal deformation law of the assembly specimen gradually becomes uniform. After the assembly specimen is compressed as a whole, the surface displacement is close to the same.

It can be observed from Figures 14 and 15 that under the two speeds, a large displacement area appears in the upper left corner and lower left corner of the specimen respectively. The main reason is that the impact load is applied from the left side of the specimen, the rock hardness is high and the rock is brittle, and the local burst occurs, resulting in the redistribution of the stress inside the assembly. The reason for the burst may be the nonuniform spatial distribution of minerals in the specimen, because of the cracks or pores causing local stress concentration. Another possible reason is that the axial load is not uniformly applied to the specimen during the placement process. After the composite specimen is further acted by impact load, cracks begin to occur in the middle of the composite specimen as the strength of the middle coal part of the composite specimen is smaller than that of the rocks at both ends. Under the continuous impact load, the cracks generated in the coal body gradually expand and extend to the rocks at both ends, resulting in large cracks, which eventually lead to the integrated fragmentation of the composite specimen. From the above analysis, it can be concluded that the rock-coal-rock assemblage can be roughly divided into three stages: uniform deformation, local deformation and overall crushing under impact load.

4.2.2. STRAIN FIELD ANALYSIS OF ROCK - COAL - ROCK COMPLEX FAILURE PROCESS

Figures 16 and 17 respectively describe the variation law of ε_{xy} principal strain field of the specimen under two different impact velocities. It can be seen from the two figures that the ε_{xy} principal strain field can fully reflect the development and variation law of cracks in the specimen.

It can be concluded from the two figures that according to the uniformity of the deformation of the assembly, the deformation of the assembly specimen under impact load can be divided into three stages: uniform deformation, local deformation and crack propagation and extension. According to the analysis results of DIC method, it can be obtained: In the first stage after the impact load, within 10 μs, the impact stress wave is reflected several times inside the rock-coal-rock assembly specimen, and the strain uniformity phenomenon appears, but this strain uniformity phenomenon is only relative. In the image, there are also some local regions with low strain and high strain randomly distributed in the assembly specimen. In the second stage after the impact load, within 10-20 μs after the impact, the strain field of the assembly has a significant change, and the strain concentration area appears in the middle region of the assembly and the range becomes larger and larger. When the strain field begins to concentrate in the local region, the tensile strain in the middle region of the assembly specimen also increases and concentrates. Figures 16 and 17 show the phenomena shown at 15 and 20 μs after stress action. The strain concentration area starts from the middle of the specimen of the assembly, mainly because the coal is located in the middle of the rock-coal-rock assembly, and the strength and hardness of the coal are relatively small compared with that of the rock. Under the impact load, the coal in the middle of the assembly will be compressed and deformed first. In the third stage after the impact load, the image analysis presented at the time point of 20 μs~30 μs in Figures 16 and 17 shows that under the continuous action of stress waves after the load, the stress concentration area in the second stage will preferentially expand into cracks and continue to extend and expand, accompanied by the continuous increase of cracks. The cracks of coal and rock mass in the composite will be connected with each other.

As shown in the image display results at 30 μs in Figures 16 and 17, although the deformation displacement and strain of the composite have many similarities under the loading strength of 8.584 m/s and 13.57 m/s with bullet impact velocity, differences are also presented. From Figure 16 to Figure 17, it can be seen that with the increase of impact load, the strain rate increases. The shorter the duration of strain from local to uniform distribution, the stronger and faster the degree of crack propagation, and the greater the degree of fracture of the assembly specimen in the later period. DIC method was used to analyze the experimental results of the assembly specimen, and the results were consistent with the law of macroscopic crack growth of the specimen. DIC method could be used to study the strain field law of the assembly before the macroscopic crack occurred.

5. CONCLUSIONS

In this paper, the dynamic evolution laws of displacement field, strain field, crack initiation, propagation and penetration of rock-coal rock assemblages under different rates of impact loading are experimentally investigated by using digital image correlation method. The changes of specimens of coal and rock assemblages over time under different loading rates are compared, and the following conclusions can be preliminarily drawn through comparative analysis:

1. The experimental data obtained by digital image correlation method and the trend of crack evolution diagram expressed by displacement and strain cloud map agree with the theory. The digital image correlation method can effectively describe the crack propagation, penetration and strain field changes of coal and rock assemblages, and is a feasible technique for studying the failure mechanism of coal and rock assemblages.

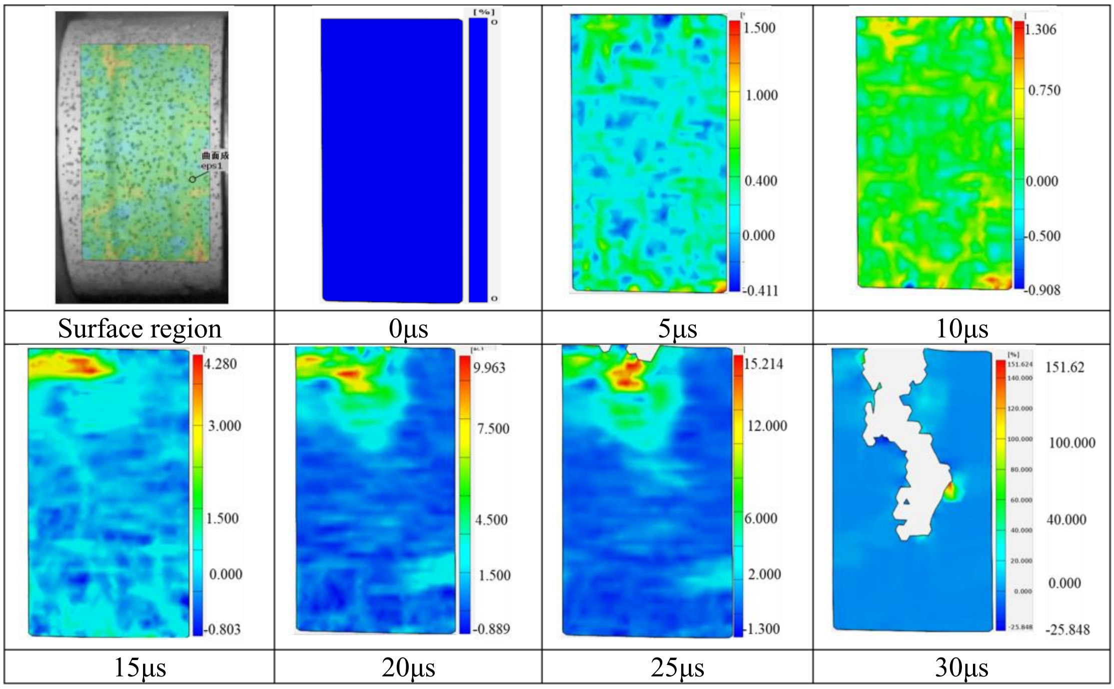

Fig. 16 Full-field strain of rock-coal-rock composite at impact velocity of 8.584 m/s.

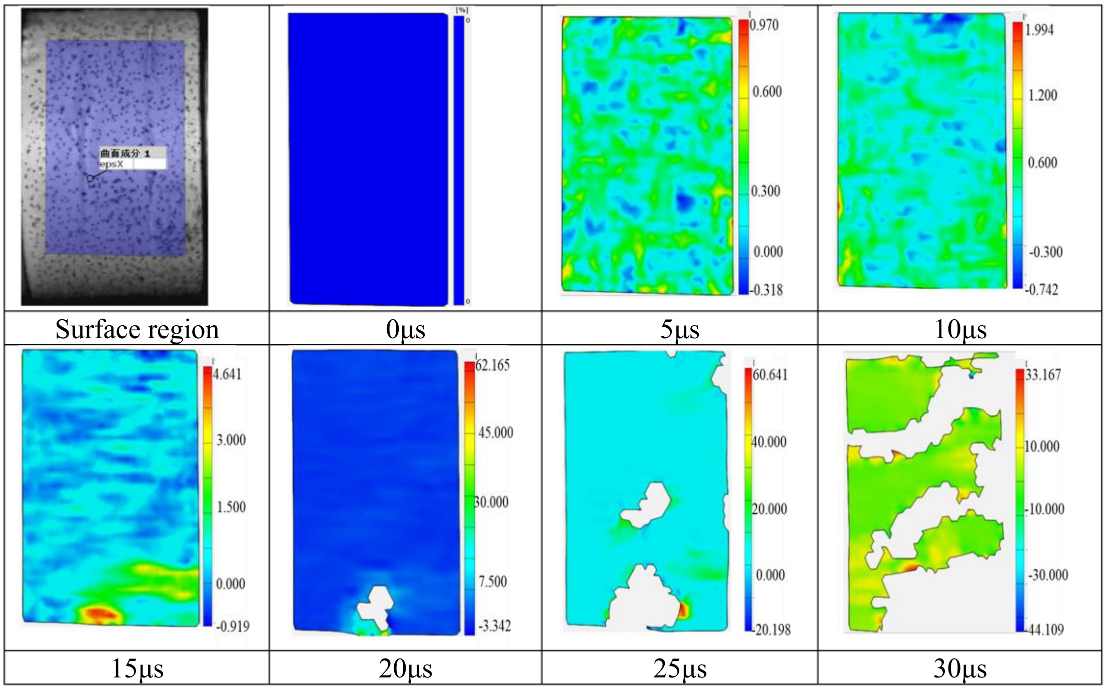

Fig. 17 Principal strain field analysis of rock-coal-rock composite with impact velocity of 13.57 m/s.

2. Under the impact load, the test results showed that the specimens of rock-coal-rock assemblage show axial splitting failure, and the cracks in the middle coal body appear first and the damage is the most serious, and the coal body also shows ejection phenomenon under high-speed impact. With the increase of the experimental strain rate, the faster the time for specimen to reach the uniform strain, the greater the speed of crack evolution and expansion, and the more obvious the degree of breakage of the specimen.

3. DIC analysis showed that the specimens underwent three stages of uniform deformation, local deformation and overall crushing. After the initial uneven deformation of the rock-coal-rock assembly, the stress wave propagates and reflects internally for many times in the later stage, and the internal deformation tends to be stable, the specimens are compressed as a whole, and the displacement tends to be consistent.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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