FRACTAL CHARACTERISTICS OF CRACK PROPAGATION IN COAL UNDER IMPACT LOADING

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Abstract

This paper studied the fractal characteristics of crack propagation in coal containing beddings under impact loading condition. Split Hopkinson pressure bar (SHPB) system was applied to determine the prepared notched semi-circular bending specimens. The high-speed camera was used to record the propagation characteristics of cracks. The image processing method and fractal dimension calculation software are combined to further analyze the effects of bedding and loading rate on the fractal characteristics of crack propagation in coal. The experimental results presented that the presence of bedding has a remarkable impact on the crack propagation. The

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crack velocity of coal samples with 45° bedding angle is of the maximum, however, the crack velocity of samples with 0° bedding angle is of the minimum. Bedding angles also have obvious influence on the fractal dimension of cracking path, the bedding angle of 45° being the largest, and those of 22.5° and 67.5° having the intermediate values, while those of 0° and 90° being the smallest. Several points of instantaneous fractal crack velocity are close to the Rayleigh wave velocity (C_r). The crack velocities of coal specimens with bedding angles of 22.5° , 45° and 67.5° are prone to the high value.

Keywords: Coal; Fractal Dimension; Bedding; SHPB; Notched Semi-Circular Bend.

1. INTRODUCTION

Coalbed methane (CBM), also known as coalbed adsorption methane or coal seam gas, is a methane-dominated gas mixture formed in the process of coalification and a kind of unconventional natural gas with coal as reservoir. In particular, according to the statistical results of the International Energy Agency (IEA), the geological resources of China's CBM buried in depth of 2000 m is about $36.81 \times 10^{12} \text{ m}^3$, and the amount of CBM resources is third in the world. However, CBM reservoirs in China are featured by low pressure, low permeability, low saturation and high adsorption, which pose a major obstacle of successfully extracting gas and carbon dioxide displacement of methane. To enhance the extraction rate of CBM, hydraulic fracturing and hydraulic slotting technologies^{1,2} are both widely employed to raise the permeability of coal mass by breaching the original structure of coal and producing cracks. As a result, it is crucial to be familiar with the fracture features and crack propagation characteristics in the procedure of extracting CBM by hydraulic fracturing.

On the other hand, studies of crack propagation in rocks under dynamic loading are of considerable significance to blasting engineering, earthquake research and rock failure process. Freund³ has extensively reviewed the previous researches on crack propagation. Dynamic fracture tests have been further conducted on homogeneous amorphous materials to research the limiting crack speeds, crack branching and fracture surface roughness.⁴ However, for brittle anisotropic and heterogeneous rock materials, especially coal material, there are almost no experiments, mainly thanks to the adversities related to carrying out such tests. Although there have been limited investigations on rock materials, it has been proved that the sample with simple geometry and a variety of optical testing instruments, rendering

possible comprehensive methods to certificate reliable results.⁵ In the field of experimental techniques, optical methods such as high-speed photography have been proved to be able to capture and record the fracture characteristics of rock-like materials.^{6–9} The strengths of this experimental approach are the simple optical patterns and high precision. The high-speed photography approach has been far used in many isotropic materials, but few studies have been conducted to monitor the fracture characteristics of natural coal material. Coal is a typical sedimentary rock, which contains complex networks of bedding planes and micro-cracks and shows strong anisotropy mechanical properties. The anisotropy of coal determines the mechanical behavior of coal mass, and reveals the danger potentials to the safe and efficient mining of coal and the extraction of CBM. Till now, scientists have devoted endeavors to investigate the effect of anisotropy on rock mechanical properties. Chenevert and Gatlin¹⁰ studied the effects of bedding plane orientation on the elastic constants and the yield strengths of three laminated rocks (sandstone, shale and limestone) and showed that bedded formations exhibit sizable directional variations in both their elastic constants and yield strengths. These researches also prove that the anisotropy exerts an obvious impact on the uniaxial compressive strength,¹¹ flexural strength,^{12,13} tensile strength¹⁴ and mode I fracture toughness of rock.^{15–18} However, in terms of previous literatures, the influence of bedding plane on the crack propagation characteristics of coal is limited. Moreover, in the process of CBM extraction, the effect of anisotropy of coal seam bedding on fracture properties and crack propagation is rarely reported. Therefore, the investigation of fractal characteristics of crack propagation and anisotropic fracture mechanics in coal seam is of great significance to enhance

the efficiency of CBM exploitation by hydraulic fracturing technology.

In addition, there are still some discrepancies between theoretical predictions and experimental findings on the crack propagation velocity of rock, and the reasons remain unclear. A good case in point is that the highest crack velocities observed in many experiments are significantly lower than the Rayleigh wave speed. A possible reason is that the current dynamic fracture theory assumes that the crack propagates along a straight line, but the propagation path of the crack is usually irregular.¹⁹ Xie and David²⁰ applied fractal theory to analyze the crack velocity and proposed a fractal kinking model to describe the irregular propagation of crack. On combining a laser gap gauge (LGG) system with strain gauge measurement, the transition of stable–unstable crack growth was observed by Dai.²¹ However, the previous studies only focused on the apparent crack velocity,²⁰ and the relationship between the fractal crack propagation velocity and the Rayleigh wave speed has not been studied.

The word “fractal” is originated from a basic paper of Benoit Mandelbrot.²² It is used to illustrate the geometry of objects that can be modeled by Euclidean geometry. According to Mandelbrot,²² a fractal is a set whose Hausdorff–Besicovitch dimension is strictly larger than its topological dimension. Many natural objects can be directly considered as fractals, e.g. cloud boundaries, coastlines, or the rough fracture surfaces in rocks. However, none of them is an actual fractal; fractal characteristics cannot be seen when a subject is observed on a sufficiently small scale. Still, as to a series of scales, the natural objects emerge frequently like fractals, and in such a situation, they may be taken as fractals. True fractal does not exist in nature, neither does true straight line nor circle.²² It is remarkable that the fractal is more suitable for the approximation of a real object than a straight line and a circle.²³ Cai *et al.*^{24–26} derived a simple relation between the fractal dimension of random walker (FDRW) and tortuosity fractal dimension (TFD) of current streamlines, and a permeability model for porous media considering the stress sensitivity based on the fractal theory. Moreover, there have been a great deal of researches concerning the contribution of the fractality of crack to the mechanics of fracture.^{19,20,23}

In this paper, the dynamic notched semi-circular bending (NSCB) tests were implemented to determine the fractal characteristics of cracking in

anisotropic coal samples. In order to get the fracture process of coal samples, the optical method of high-speed photography was employed. The image processing software and fractal dimension calculation software were utilized to quantitatively analyze the fractal characteristics of crack propagation in coal. Specifically, the differences of fractal dimension, cracking length and propagation velocity of crack propagation in coal specimens with various bedding angles under different impact velocities were contrasted and analyzed.

2. EXPERIMENTAL SETUP

2.1. Specimen Preparation

Coal blocks were gathered from No. 11 coal seam in the Xinzhouyao coal mine in Datong city, Shanxi province, China, as shown in Fig. 1. First, the coal block was made into cylindrical sample with diameter of 50 mm and thickness of 25 mm. Then, the coal sample was cut into two semi-circular specimens from the center of the cylinder sample and a groove was made in the middle. Figure 2 shows the geometric size and bedding angle (angle between the bedding and loading direction) of the sample and the SHPB loading device, respectively. The geometric parameters of the sample are as follows: the groove width $e = 1$ mm; groove length a is set to 4, 7 and 10 mm, respectively; the distance between two supporting rods $S = 30$ mm; diameter $D = 50$ mm; the bedding angle is set to five groups, 0° to 90° , each with an interval of 22.5° . The bedding angle of samples at the same group is kept as much similar as possible, and the impact velocities were varied from 3.50 m/s to 6.25 m/s. The different experimental factors are designed to investigate the influence of bedding angle, impact velocity and groove length on the crack propagation characteristics in coal.

It should be noted that the selected coal samples are bituminous coals. The vitrinite reflectance (0.76–0.85%), volatile matter (25.0%), moisture content (4.0%), fixed carbon (68.7%) and ash (2.3%) were determined by the coal proximate analysis.^{27,28} In addition, the physical and mechanical parameters of coal samples and the test results of the elastic wave velocity are listed in Tables 1 and 2, respectively.

2.2. SHPB Test

The SHPB loading device includes a striker bar, an incident bar, a transmitted bar and an absorbed

Fig. 1 Location of the Xinzhouyao coal mine. (a) Boundary of Xinzhouyao coal mine with contour lines and sampling work face. (b) Location of the Xinzhouyao mine in Shanxi Province.

Fig. 2 Schematic view of dynamic testing method about NSCB specimen and SHPB system. (a) Schematic and dimensions of NSCB specimen. (b) Photographic view and bedding angle (θ) of coal sample No. 3432. (c) Schematic of the setup of SHPB system.

bar, as shown in Fig. 2c. The length of each part is 400, 2000, 2000 and 1000 mm, respectively, and the diameter is all 50 mm. During the experiment, the coal samples are sandwiched between the incident bar and the transmitted bar and the crack propagation and rotation of the specimen were

recorded by a high-speed camera. The strain wave produced by the incident bar is recorded as $\varepsilon_I(t)$; a part of the strain wave is reflected at the interface between the incident bar and the specimen, which is recorded as $\varepsilon_R(t)$; and the strain wave eventually propagated to the transmitter bar is recorded

Table 1 Summary of the Physical and Mechanical Properties of Datong Coal and the SHPB-Bar.

Material	ρ (kg/m ³)	c (MPa)	φ (°)	E (GPa)	ν	σ_t (MPa)	σ_c (MPa)
Coal	1301	7.85	32.64	2.38	0.38	1.75	27.64
35CrMn Steel	7800			200	0.28		

Note: ρ -density; c -cohesion; φ -friction angle; E -Young's modulus; ν -Poisson's ratio; σ_t -tensile strength; σ_c -uniaxial compressive strength.

Table 2 The Elastic Wave Velocities Parameters of Datong Coal with Different Bedding Angles.

Bedding Angle (°)	Longitudinal Wave Velocity (m/s)	Shear Wave Velocity (m/s)	Poisson's Ratio	Elastic Modulus (GPa)	Rayleigh Wave Velocity (m/s)
0	1993 ₉ ± 174	824 ₉ ± 48	0.3955 ₉ ± 0.01	2.49 ₉ ± 0.31	775.68 ₉ ± 47
22.5	2016 ₉ ± 194	810 ₉ ± 25	0.3992 ₉ ± 0.03	2.427 ₉ ± 0.144	762.65 ₉ ± 24
45.0	1901 ₉ ± 75	800 ₉ ± 32	0.3915 ₉ ± 0.01	2.354 ₉ ± 0.17	752.07 ₉ ± 29
67.5	1821 ₉ ± 151	831 ₉ ± 87	0.3614 ₉ ± 0.05	2.498 ₉ ± 0.43	777.09 ₉ ± 77
90.0	1726 ₉ ± 128	770 ₉ ± 28	0.3735 ₉ ± 0.02	2.123 ₉ ± 0.176	721.51 ₉ ± 27

Note: The data in the table are expressed in the form of "Average value_{Number of samples} ± Standard deviation".

as $\varepsilon_T(t)$. Due to the free access to the front of the striker bar, pulse-shaping techniques using a thin ductile metallic disc⁵ or a dummy specimen²⁹ can be used to shift the shape of the impact pulse. The pulse-shaping technique for SHPB system was extensively reviewed by Frew *et al.*³⁰ During the SHPB test, a contrast experiment on two types of pulse shaper including the copper disc and rubber disc was conducted, and the pulse shapers were tied on the center of the incident bar. Contrasting two resulting waveforms, it was found that the rubber disc pulse-shaper method could significantly relieve the dispersion effect compared to the copper shaper. Therefore, rubber disc was adopted ultimately as the pulse shaper.

3. RESULTS AND DISCUSSION

A total of 135 samples were tested, and only 81 were successful for dynamic fracture of coal. It should be noted that, in accordance with the recommendations of the International Society for Rock Mechanics (ISRM),³¹ the dynamic force balance of all experiments has been examined, and the results exhibit that the condition meets all of the tests. Figure 3 presents the force balance results of coal samples with different bedding angles during the experiment.¹⁸ It can be seen that the force at both ends of the specimen is basically in a state of balance during the experiment and there are considerable variations in the magnitude of the force due to the different loading conditions. Thus, the inertial

effects induced by the stress wave can be eliminated as there is no global force gap in the sample.

3.1. Crack Initiation and Propagation Process

Figure 4 shows the typical image processing of irregular crack propagation of NSCB coal sample under the dynamic loading. Figure 4a shows the appearance of the coal sample before loading recorded by high-speed camera, Figs. 4b–4e indicate the final morphology of crack propagation in coal, image enhancement based on histogram equalization method, binary image of coal sample and the extraction of crack path in coal sample, respectively.

The sequence shown in Fig. 5 represents the frames of five representative features of coal specimens with different bedding angles (0.0°, 22.5°, 45.0°, 67.5° and 90.0°). The first image of each group is correspondent with the scene when the incident pulse reaches the interface of the incident bar and the sample and the crack begin to initiate. In general, the crack propagation paths of coal with the 0° and 90° bedding angles are straighter than the other groups, and the coal with 45° bedding angle is more curved. The crack propagation within the coal sample with the bedding angle of 67.5° shows some discontinuity. In addition, the apparent crack propagation velocity can be calculated based on the time and the distance of the crack growth. The apparent crack propagation velocities of five coal specimens

Fig. 3 Dynamic force balance check for five typical dynamic NSCB tests on the Datong coal with different bedding angles. (a) Sample No. 1231 with the bedding angle of 0° , notch length of 7 mm and the impact velocity of 3.879 m/s. (b) Sample No. 3151 with the bedding angle of 22.5° , notch length of 7 mm and the impact velocity of 3.740 m/s. (c) Sample No. 2331 with the bedding angle of 45.0° , notch length of 7 mm and the impact velocity of 3.591 m/s. (d) Sample No. 3432 with the bedding angle of 67.5° , notch length of 7 mm and the impact velocity of 3.827 m/s. (e) Sample No. 1111 with the bedding angle of 90.0° , notch length of 7 mm and the impact velocity of 3.931 m/s.

Fig. 4 Image processing of fractal crack propagation of NSCB coal sample under the dynamic loading. (a) Image of NSCB coal sample before loading recorded by high-speed camera. (b) The morphology of crack propagation in coal. (c) Image enhancement based on histogram equalization method. (d) Binary image of coal sample (ZOI-zone of interest). (e) Extraction of crack path in coal sample.

with different bedding angles are 119.32, 127.27, 127.27, 109.09 and 119.32 m/s, respectively. The average value is 120.45 m/s and the ratio of maximum apparent crack propagation velocity to the Rayleigh wave velocity is 0.159. According to the previous experimental results,^{32–34} the crack propagation velocities of dynamic three-point-bending Zhaogezhuang coal specimens, NSCB Laurentian

granite specimens and NSCB Fangshan marble are 234.03–324.88, 268–355 and 680 m/s, respectively. Thus, it can be concluded that the apparent crack propagation velocities of Datong coal are less than that of Zhaogezhuang coal as well as Laurentian granite, being approximately 16.04–18.72% of that of the Fangshan marble. This may be due to the different test rock materials or the methods.

(a) Bedding angle = 0° , Impact velocity = 4.681 m/s, Crack length = 4 mm, Specimen No. 1221.

(b) Bedding angle = 22.5° , Impact velocity = 4.623 m/s, Crack length = 4 mm, Specimen No. 3342.

(c) Bedding angle = 45° , Impact velocity = 3.902 m/s, Crack length = 4 mm, Specimen No. 2831.

(d) Bedding angle = 67.5° , Impact velocity = 4.513 m/s, Crack length = 7 mm, Specimen No. 3831.

Fig. 5 Dynamic crack propagation process of coal with various bedding angles.

(e) Bedding angle = 90° , Impact velocity = 5.385 m/s,
Crack length = 4 mm, Specimen No. 1141.

Fig. 5 (Continued)

The above-mentioned results of average crack propagation velocity of Datong coal are analyzed based on the traditional experimental analysis method. But, it is noted that this calculation method only considers the motion of the crack tip using apparent crack velocity, despite the irregularity (or fractality) and instantaneity of crack propagation, which is the same in essence as the method for calculating the crack velocity by using the strain gauge technique in previous experiments.^{32,34}

Through the analysis of the crack propagation velocity in this work and the previous experimental results,^{5,32–34} it is safe to draw a conclusion that the apparent crack velocity is much smaller than the Rayleigh wave velocity. This may be due to the fractal characteristics of crack propagation.²⁰ Therefore, the fractal crack propagation velocities of the five specimens are also calculated, being 122.65, 136.26, 156.95, 142.21 and 124.36 m/s for different bedding angles, respectively. The ratio of maximum fractal crack propagation velocity to the Rayleigh wave velocity is 0.207, and the ratio range between the apparent crack propagation velocities and the fractal crack propagation velocities of five coal specimens is 0.767–0.971. Thus, it can be concluded that the fractal crack velocity is larger than the apparent crack velocity, but it is still far less than the Rayleigh wave velocity.

3.2. Fractal Dimension of Crack Propagation Path

In order to further explore the effects of bedding angle and impact velocity on the fractal dimension of crack propagation in coal, the image processing method and fractal dimension calculation software are combined to analyze the data. The figure of the crack-path fractal dimension D is a quantitative

parameter describing the degree of curvature of the crack propagation. The higher fractal dimension responds to a more curved crack path. In this research, the fractal dimension of the crack propagation path in coal samples is calculated by box-counting method.¹⁹ According to this method, firstly, the length of the extracted crack propagation image is changed to 1 by the dimensionless method, and the image is divided into regular square grids with scale δ , then the number of meshes covering the image region is calculated as $N(\delta)$. Changing the scale δ may give different values of $N(\delta)$. Therefore, the fractal dimension D of the crack path can be accumulated by the relationship: $D = \log N(\delta) / \log(1/\delta)$. Based on the above method, the fractal dimension of the crack paths are calculated as the scale increases from 0.2 mm to 2.0 mm.

Fig. 6 Plot of box-counting method applied to curved crack of typical fractured NSCB coal specimen, number of occupied boxes $N(\delta)$ plotted versus box size (δ), slope of line fit to data is fractal dimension D .

Fig. 7 Fractal dimension of crack propagation in coal specimens with different bedding angles.

Figure 6 shows the box-counting method applied to curved crack of fractured NSCB coal specimen. The linear fitting function is $\log N(\delta) = -1.2759 \log \delta + 2.5281$, and the fractal dimension is 1.2759. Figure 7 shows the characteristic of fractal dimension of crack propagation in coal specimens with different bedding angles. In general, the fractal dimension of crack propagation in coal with bedding angle of 45° is the largest. The average fractal dimension of crack propagation in coal specimens with bedding angles of 0°, 22.5°, 45.0°, 67.5° and 90° are 1.2749, 1.3025, 1.3692, 1.347 and 1.3001, respectively. Thus, the bedding angles have obvious influence on the fractal dimension of crack path, i.e. the bedding angle of 45° is the largest, and those of 22.5° and 67.5° take the second place, while those

of 0° and 90° are the smallest. Moreover, the results indicate that the fractal dimension dispersion of coal specimens with the bedding angles of 90° is the smallest, while the fractal dimension dispersion of coal specimens with the bedding angles of 0° is the largest.³⁵

Figure 8 shows the fractal dimension of crack propagation in coal specimens. It can be found that the fractal dimension of crack propagation in coal specimens with bedding angles of 0° and 90° increases with the increase of impact velocity. However, the impact velocity has limited influence on the fractal dimension of crack propagation in coal, when the bedding angles are 22.5°, 45° and 67.5°. This result demonstrates that the impact velocity has significant influence on the fractal dimension of crack propagation in coal when the impact direction is parallel or perpendicular to the bedding plane.

3.3. The Instantaneous Characteristic of Fractal Crack Propagation

The instantaneous crack length and velocity of coal specimens in a short period of time are obtained using the high-speed camera and image processing method. Figure 9 shows the crack length, velocity and acceleration of No. 1141 coal specimen. The crack begins to propagate when the time $t = 0$, and the crack tip position (i.e. crack length) is defined by $L(D, t)$ for $t > 0$. The fractal crack trace $L(D, t)$ can be approximated by a polygonal curve of a fractal interpolating function $L(t)$. Function $L(t)$ can be divided into four stages, the growth of crack length in stage I is slow, and the crack length increases rapidly in the stage II, while the growth rate of crack length is similar in the stages III and IV. This conclusion is consistent with the previous theoretical analysis.²⁰ In terms of time, the peak of velocity and acceleration alternated, the acceleration reached the peak before the velocity reached the peak for the same crack. Acceleration represents the change of driving force, when it firstly reached the peak, the driving force was the largest, while the crack propagation continuously accelerated under the application of driving force. This result is consistent with the conclusion of Yang *et al.*³⁶

Figure 10 shows the crack length and propagation velocity of coal specimens with different notch lengths. It can be seen that the variation trend of the crack length of coal specimens with different notch depths is basically the same. All the functions

Fig. 8 Fractal dimension of crack propagation in coal specimens with different bedding angles under various impact velocities.

Fig. 9 The crack length, velocity and acceleration of No. 1141 coal specimen. A polygonal curve of a fractal interpolating function $L(t)$, approximating the actual crack tip trajectory of fractal crack trace, $L(D, t)$.

Fig. 10 The crack length and propagation velocity of coal specimens with different notch lengths. (a) and (b) The crack propagation of coal specimens with notch length of 4 mm. (c) and (d) The crack propagation of coal specimens with notch length of 7 mm. (e) and (f) The crack propagation of coal specimens with notch length of 10 mm.

Fig. 10 (Continued)

of crack length can be divided into several stages and can be replaced by the interpolation function. In addition, as can be seen from Figs. 10b and 10d, several points of instantaneous fractal crack velocity are close to the Rayleigh wave velocity (C_r). This conclusion confirms the previous hypothesis from the experimental point of view, i.e. the reason why the crack propagation velocity is much smaller than the Rayleigh wave velocity may be that the fractal and instantaneous effects of the crack propagation are not taken into account.^{19,20} The maximum values of crack velocities of coal specimens with notch lengths of 4 mm and 7 mm are in the range of 25–50 μ s and 50–75 μ s, respectively. However, the maximum values of crack velocities of the coal specimens with the notch lengths of 10 mm are lower than those of the coal specimens with the notch lengths of 4 mm and 7 mm. It has two peaks, which are in the range of 25–50 μ s and 75–100 μ s. Overall, the crack velocities of coal specimens with bedding angles of 22.5°, 45° and 67.5° are prone to the high value. It also shows that the bedding angle has a significant influence on the instantaneous fractal crack velocity.

4. CONCLUSIONS

The purpose of this research is to study the fractal characteristics of crack propagation in coal containing beddings under impact loading. The dynamic fracture processes of 81 samples were successfully measured. The main conclusions are as follows:

- It has been found that the presence of beddings has a significant impact on the crack propagation. The crack speed of coal with the 45° bedding

angle is larger than those with other bedding angles, and the crack speed of coal with the 0° bedding angle is the smallest. Moreover, the fractal crack velocity is larger than the apparent crack velocity, but it is still far less than the Rayleigh wave velocity.

- In terms of time, the peak of velocity and acceleration alternated, the acceleration reached the peak before the velocity reached the peak for the same crack.
- Several points of instantaneous fractal crack velocity are close to the Rayleigh wave velocity (C_r). It explains the previous hypothesis from the experimental point of view. The reason why the crack propagation velocity is much smaller than the Rayleigh wave velocity may be that the fractal and instantaneous effects of the crack propagation are not taken into account.
- The crack velocities of coal specimens with bedding angles of 22.5°, 45° and 67.5° are prone to the high value.

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